Level Schedule Implementation in Unstable Manufacturing Environments

by

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Abstract

American Axle & Manufacturing Inc. (AAM), headquartered in Detroit (MI) is one of the major Tier 1 suppliers in the automotive industry. The main challenge in AAM plant 2 is production rate unstability due to downtime, quality, changeover and absenteeism issues. The company is currently making a major effort to reduce this unstability.

This thesis describes some of the systems which have been implemented in order to improve the inventory management policy in this factory. The document is structured around three main topics: research on the operations and materials management policy in Plant 2, design of new lean management systems (level scheduling and visual management) and design of new Operations Research-based production planning tools to coordinate multiple mixed model production lines in an unstable manufacturing environment.

Special emphasis is placed on the role of execution for true improvement and the challenges faced by the implementation team in this initiative.

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Chapter 1

Overview

1.1 Introduction

"Their process is much more simple" was the answer that Mark Dauer, value stream manager at American Axle Detroit Gear & Axle (DGA) gave to those who compared operations between Plant 2 and Plant 6. *"they have fewer products, fewer customers, fewer operations and, most importantly, more stable component lines"*.

Plant 6 had achieved an enormous success in 2006 in the implementation of lean processes and systems. Finished goods inventory had decreased by 50%, cost of quality by 50% and labor force moral had increased up to historical levels. Many pointed the levelling system installed in this plant as the main source of all these benefits and wondered why a similar success could not be achieved by Plant 2, source of 40% of the revenues on the site (and a similar percentage of the costs).

Over the years there had been several attempts to implement Heijunka systems in Plant 2 but all had failed for different reasons, among them, the lack of experience and trust in Lean concepts across the site. This tendency changed in late 2006 and early 2007, when number of new lean initiatives were successfully implemented, and some wondered whether it was the right time to try it again.

"This time", said Tim McNelis, leader of the Lean Deployment Group in the site, *" we cannot let it die. If we do, all the inertia we have created in the plant will die with it. Everyone in the plant has to be involved. We need support of operators, union, plant manager and upper management."*

This thesis describes some of the material flow improvements carried out in Plant 2 during the time the author was in the site: June 2007 to December 2007. It also describes the experiences of the team that leaded this initiative and some of the major take-aways collected by this team. Results are provided for most of the improvements described in this document too.

The rest of the document is organized as follows: Chapter 2 provides a short overview of Toyota Production System and other manufacturing concepts required to fully understand the initiatives described in the following chapters. Chapters 3 and 4 are the core of the document. The former concentrates on the Heijunka system and its impact in the operations in the assembly line area of the plant. The latter concentrates in two different efforts dedicated to improve material flow in the component groups area and in a new technique to schedule unstable mixed model manufacturing systems. Take-aways and final analysis of the next steps are discussed in the conclusion. The remaining sections of this chapter provide some context about American Axle's history, business challenges and opportunities and the operations in Plant 2.

1.2 General information

American Axle & Manufacturing Inc. (AAM), headquartered in Detroit (MI), is one of the major Tier 1 suppliers in the automotive industry. The company has over 80 years of experience in the design, engineering and manufacture of chassis systems, drivetrain and driveline systems and forged products for buses, trucks, passenger cars and sports utility vehicles (SUVs). The company's product portfolio includes driveshafts, chassis modules, chassis and steering components, axles, transfer cases, power transfer units, crankshafts, driving heads, metal-formed products and transmission parts. In fiscal 2006, AAM posted net sales of US$3,191.7M, a 5.8% decrease when compared to US$3,387.3 in fiscal 2005. Several trends are relevant to AAM's current and future.

Globalization The global automotive industry is structurally changing, with approximately 95% of all automotive industry growth occurring outside of the U.S. AAM's product launches in 2007 reflected its tendency to follow industry trends through geographic diversification. The Changshu, China facility launched production of rear-drive modules for the Beijing Benz DaimlerChrysler (BBDC) 300C sedan and the SsangYong Motors Chairman sedan to be produced in Seoul, South Korea. The Guanajuato (Mexico) facility launched the first high-volume application of AAM's patented, electronically controlled SmartBar stabilizer system for the 2007 Jeep Wrangler Rubicon.

Customer diversification The company is dependent on two of its key customers for a major part of its sales. Specifically, GM contributed to 76% and Daimler contributed to 14% of AAM's total sales in fiscal 2006. This makes the company highly vulnerable to fluctuating production volume and the like at the customer's end. On the other hand its expertise in driveline systems and related modules has enabled it to clinch many new key contracts from its recently extended customer base, which includes Hino, Jatco, Harley-Davidson, Koyo, Audi, Nissan and Ssang Yong.

Increasingly environmentally concerned market The shift in market preference to all-wheel drives (in passenger cars and crossover vehicles) is a favorable development for AAM, given its strengths in developing technologically advanced driveline products and systems. However, excessive dependence on this market is not desirable, considering the high commodity costs, pricing pressures and bankruptcy status of certain OEMs. Moreover, demand is shifting from SUVs to crossover vehicles and smaller passenger cars.

Increasing bottom line Rising fuel and energy costs and the rise in steel and other metal costs pose a serious threat to the company's performance. These factors have already driven several suppliers in the US to file for Chapter 11 bankruptcy protection over the last three to four years. AAM has embraced lean as methodology to reduce the bottom line and provide lower cost of quality.

1.3 American Axle Detroit Gear & Axle

The Detroit Gear & Axle (DGA) complex consists of approximately 2,600,000 square feet of manufacturing floor space located on 84.9 acres of land in the cities of Detroit and Hamtrack. The facility was built in 1917 when the Cadillac Motor Company decided to build a complex to manufacture aircraft parts for the war effort. After the war, the complex was called the Chevrolet Detroit Gear & Axle Plant and became a leading manufacturer in the automotive industry using the latest technology in machinery, materials and design. For over 70 years, the complex was part of Chevrolet Division and then of General Motors. But, on March 1994, American Axle & Manufacturing purchased it. General Motors is still the main customer for AAM's gear and axle products.

1.3.1 DGA Plant 2

Plant 2 is the main building in the Detroit Gear & Axle complex. Operations in plant 2 are complex. As a high volume production facility, it has enough capacity to machine the components and assemble four thousand axles per day. As of June 2007, it provides approximately 40% of American Axle's revenues. The assembly area is responsible for three different families of pickup and SUV rear axle models: G-6, G-9 and G-10. The component groups are responsible for machining and welding all the main components: carriers, tubes and shafts. Additionally, it supplies sub-assemblies to other AAM plants such as tubes or third members for the G-3 family.

1.3.2 Assembly groups

A typical axle parts breakdown is described in figure 1.1. As it can be observed, the axle assembly process is complex and can be separated in two stages: third member and final assembly.

The first stage provides a sub-assembly called "3rd member" (3M) which contains the gear-set mechanism and the carrier that covers it. 3Ms can be assembled in either of two lines called SW and NW and are delivered to the final assembly process in racks of 18 pieces which can only be transported by fork-lift. The racks are held in an area called "3rd member bank" (3MB) which is capable of holding the demand for half a day approximately.

The final stage of the assembly process, called final assembly line and referenced with the symbol (LL), consists on the connection of 3M with tubes, shafts and brakes. The first operation, called slug welding, welds 3M with tubes and is composed of two robots working in parallel. Change-overs are long in each robot but the robots can be alternated to effectively reduce change-over time to zero for the rest of the line. Unfortunately, each robot cannot keep the speed of the assembly line individually and some backup inventory needs to be stored for change-overs. Final axles are grouped in racks of 8 to 6 pieces depending on customer needs.

There is a significant difference in capacity between LL and any individual 3M line which forces managers to run LL 24 hours a day (3 shifts) and NW and SW to run only 16 hours each (two shifts). This mismatch in capacity is the source of additional WIP requirements in the 3MB.

1.3.3 Components

Figure 1.1 describes most of the operations carried out in Plant 2. As it can be observed, an axle is composed of a large amount of parts and sub-parts. Most of them are out-sourced to external part suppliers but the main parts are machined in place before the final assembly process. They are:

- Ring and pinions (gear sets). This piece determines the amount of power that can be transferred through the axle. The axles within each family differentiate based on the case and ring and pinion they use. There are four main types of ring and pinions: 10:41, 11:41, 12:41 and 13:42. They are supplied from a nearby internal supplier and they don't need any additional work before final integration in a 3M sub-assembly.

- Cases. Once integrated with the carrier, this piece insulates the ring and pinion mechanism from external agents. There are two case types: the open case, which is machined in one of the component lines; and the locker case, which is bought from an outside supplier. Locker cases have the added

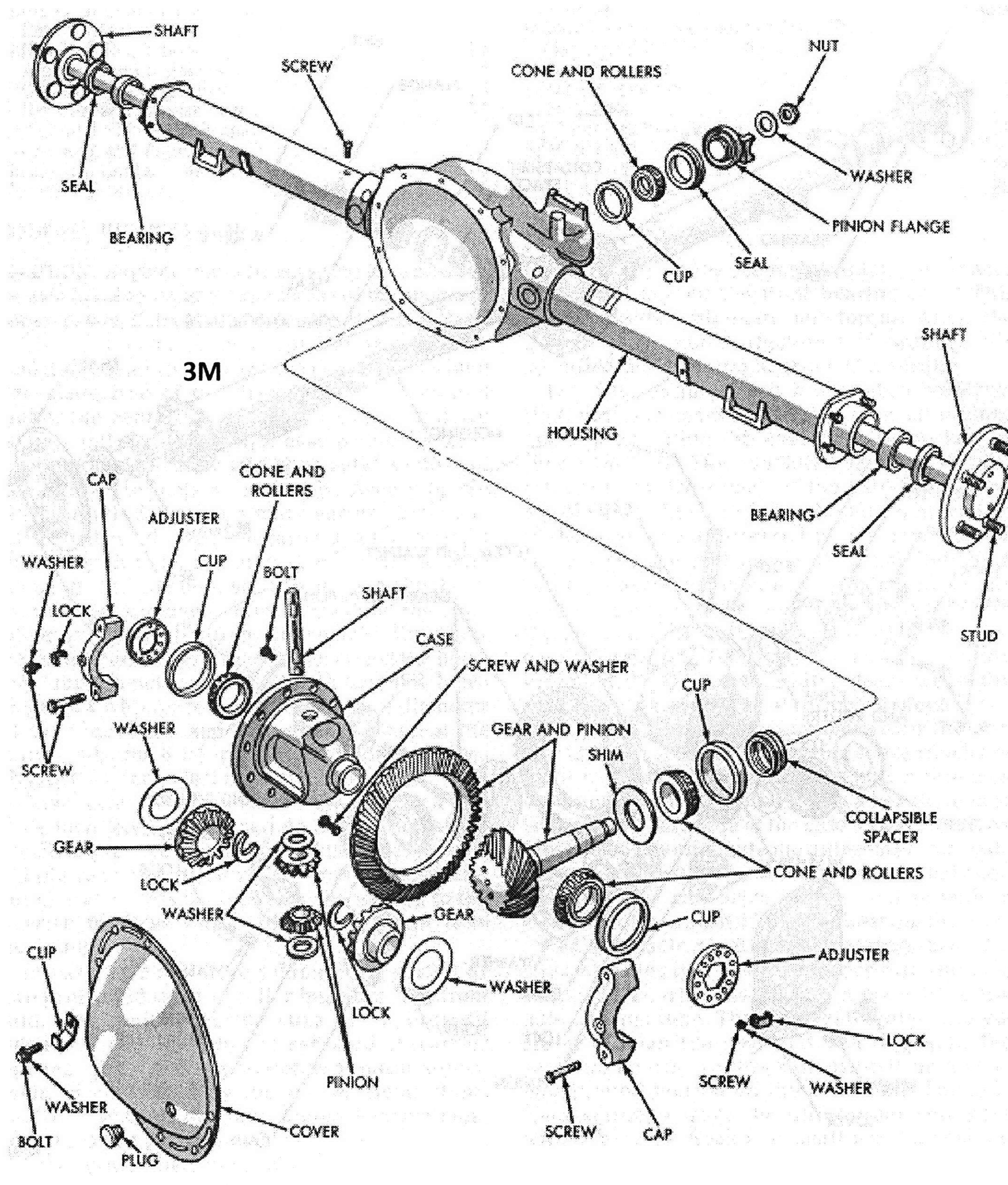

Figure 1.1: Axle assembly process. Adapted from www.dippy.org (4/30/2008)

feature that they transfer the power to the opposite wheel when one of them is sliding, preventing the truck from slippery obstacles.

- Carriers. This piece holds the ring and pinion mechanism. There are three main carrier types, one for each axle family. Once it is integrated with the case and ring and pinion mechanism, the whole system forms a 3M.

- Tubes. There are three main types of tubes, one for each axle family. The G-9 family has two tube subtypes: the G-9V and the G-9NV. All of them are bought to external suppliers but need to go through a welding and machining process before they can be integrated with the 3M in the first stage of the assembly process: the slug welding area.

- Shafts. There are three main types of shafts which are bought to an internal supplier responsible for the forging operation. Shafts need to go through a machining operation before being integrated in the final assembly line.

- Brakes, calipers and all the other, more simple elements are bought from external suppliers and don't usually generate any materials management issues.

1.3.4 Component groups

Component lines in plant 2 are responsible for 60% of the value generated in this plant. They carry out most of the operations needed between the forging operation and the final painting and shipping process. As figure 1.2 reflects, even though there is significant complexity in the material flow in this plant due to the multiple combinations of gear sets, carriers and brakes, all axle models need to go through the same process. The component lines are grouped in jobs attending to the component they operate on.

Shaft machining job This job is comprised of four different machining groups. These groups have machines that mill, chamfer, bolt and finish the shafts in order to prepare them for the assembly process. Three of them are dedicated to the G-9 and G-10 families and another one is in charge of alternating between the G-6 family and the G-3 family.

Tube welding and machining job This job is comprised of two welding and twenty five machining groups. The welding area is composed of six machines, three for each for the two main axle families: the G-9 and G-10. The tubes for G-6 family only need to be machined before final integration. They don't need a welding operation.

As described in the previous section, the G-9 family has two different groups, G-9V and G-9NV, according to the type of tube they require. The welding operation is different for the tubes of each group. One of the welding machines is permanently assigned to the most demanded G-9NV group whereas the other two can alternate between both groups with a minimal changeover time. The machines for the G-10 family can operate on all sub-types.

Carrier machining job This job is comprised of three different production lines, one of them feeds parts to an internal customer plant and is not considered in this study. The other two can process all three families of carriers (G-9, G-6 and G-3), the managers leverage the fact that G-9 is the high-volume family and keep a production line permanently assigned to this product. The other production line is constantly alternating between all three products. Change-overs take long and the job doesn't have enough capacity for peaks in demand.

1.4 Operational challenges

1.4.1 Assembly area

Historically, there had been several lean initiatives in the assembly area. While many of them achieved a major impact on the operations, as of June 2006, there was still room for improvement in material flow and production stability.

For a variety of reasons, the final assembly line was usually forced to deviate from its schedule. This reflected in the size of the finished goods inventory. The final assembly line's demand communicated to all supplier groups had more variability than the one provided by customers. This phenomenon, called 'bull-whip effect' [Lee(1997)], had significant influence on all the final assembly line's internal and external suppliers.

While part of this problem was due to the inherent unreliability of the machining processes, it was not difficult to find situations where the root cause was inefficiencies in material planning and information flow. In order to solve these issues new materials and information flow processes based on a Heijunka board and kanban systems were established. Chapter 3 is dedicated to this initiative and the challenges faced by the implementation team.

1.4.2 Component groups

Even though all component groups run were scheduled according to an inventory replenishment policy, the tube and carrier jobs were pointed as the source of most of the schedule deviations in the final assembly line. While part of the reason for this behavior was that these processes were inherently unstable, it was found that, in many cases, material flow and requirements communication was the root cause of unavailability of some parts in the final assembly line.

In the tube job, material requirements were not being communicated efficiently through the line and interruptions in the supply were frequent. Change-overs were dictated by production supervisors which were overloaded with quality control and labor management issues. Decisions were based on information which was updated only once per day and the lead time and multiplicity of operations in this group made it difficult to manage.

In the carrier job the issue was the length of change-overs. The capacity of this group was almost completely utilized and change-overs were reflected in overtime during the weekends. Weekly batches for each product were run in order to minimize overtime. Unfortunately this strategy required large amounts of WIP inventory and the supervisors of this job did not have the tools to design a schedule that minimized inventory requirements during the week.

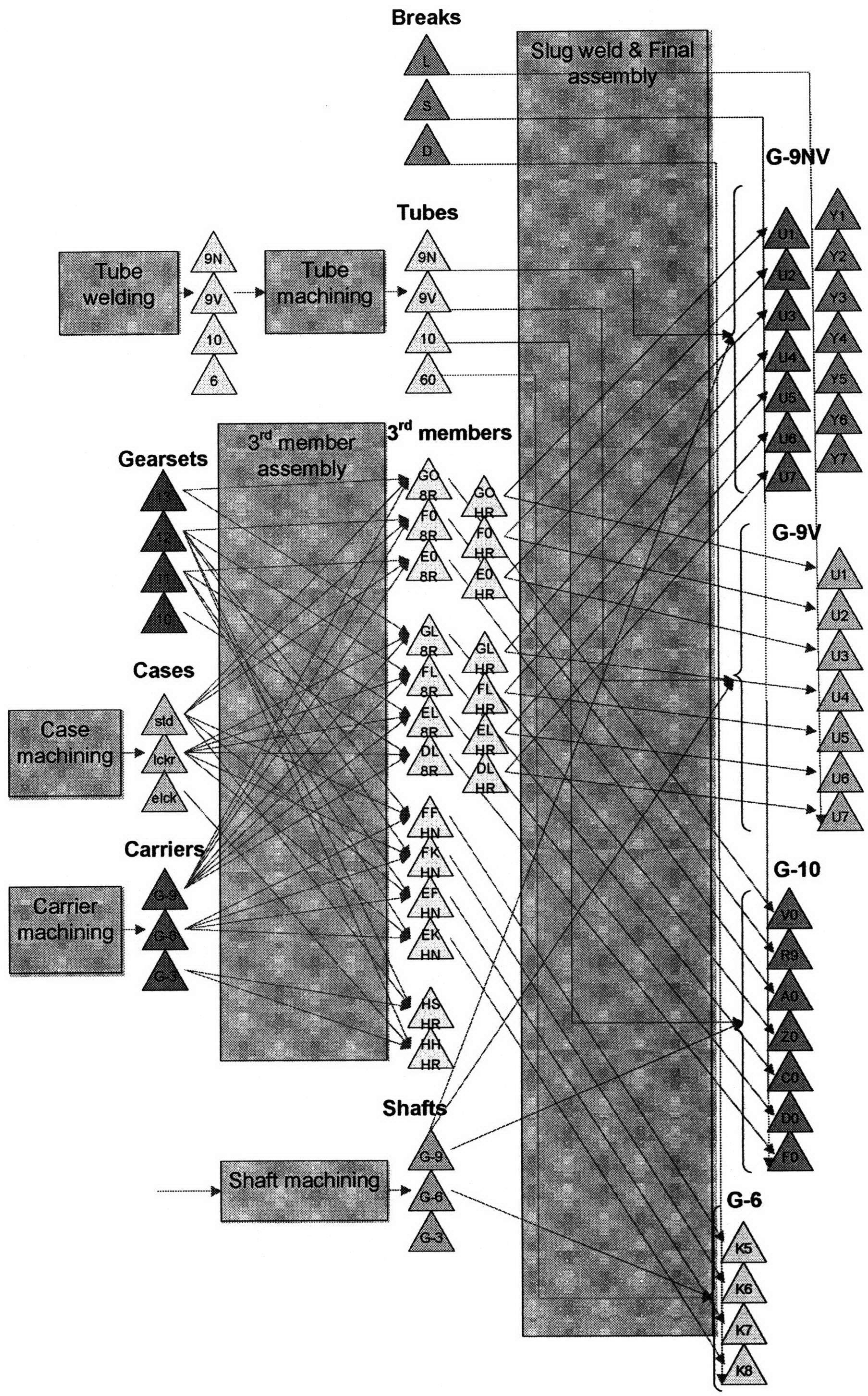

Figure 1.2: Plant 2 operations

Chapter 2

State of the art

2.1 Introduction

This chapter describes some of the main concepts in manufacturing systems' literature. Its intention is to provide the reader with an introduction into the state of the art in schedule and material flow systems for manufacturing environments such as those described in previous chapter.

The first section provides an overview into Toyota Production System. Sections 2 and 3 concentrate on the main elements of this system discussed in chapter 3: Heijunka and Kanban. Section 4 discusses planning systems in modern manufacturing environments and the perspective of TPS experts on them. Finally, the conclusion provides some insight into how these concepts will be used in the following chapters.

2.2 Toyota Production System

Toyota Production System (TPS) is the philosophy which organizes manufacturing and logistics at Toyota, including the interaction with suppliers and customers. TPS is a major part of the more generic "Lean manufacturing". It was largely created by the founder of Toyota, Sakichi Toyoda, his son Kiichiro Toyoda, and the engineer Taiichi Ohno; they drew heavily on the work of W. Edwards Deming and the writings of Henry Ford.

Value is truly the central focus of TPS. By defining and understanding value, TPS has evolved to help companies maximize value. In this system all activities relating to the manufacturing process are classified as adding value or waste.

TPS has been described as a set of tools with the goal of maximizing value for the customer: Value Network, Theory of Constraints, Six Sigma, Statistical Process Control, the Seven Sources of Waste, SMED, Kaizen, Poka-Yoke, 5S, Cellular Manufacturing, etc. The tools used to identify and minimize non-value adding activities make up TPS. However TPS is not a static system, rather it allows for continued change and improvement. The true brilliance in TPS is not the tools and techniques in existence, but the underlying system that allows for new techniques to be understood and created.

Toyota was able to greatly reduce lead time and cost using TPS, while improving quality at the same time. This enabled it to become one of the ten largest companies in the world. It is currently as profitable as all the other car companies combined and became the largest car manufacturer in 2007. TPS spreads as other companies try to adopt the system but, even nowadays, Toyota's practices keep being the main reference in manufacturing.

There is a significant amount of literature related with lean manufacturing and TPS [Smalley(2004), Carlino & Flinchbaugh(2005), wikipedia(2008)] and Toyota leadership style [Spear(2004)]. Nevertheless, the present chapter is going to concentrate in the concepts that relate to the problems presented in chapter 1: Production levelling, material flow, kanban systems and heijunka boards.

2.3 Kanban Systems

From [Smalley(2004)]

> ...Continuous flow of materials and products in any production operation is a wonderful thing, and lean thinkers strive to create this condition whenever possible. The reality of manufacturing today and for many years to come, however, is that disconnected processes upstream will feed activities downstream. Additionally, many internal processes are currently batch oriented and function as shared resources. The major challenge in this situation is for downstream processes to obtain precisely what they need when they need it, while making upstream activities as efficient as possible. This is where leveled demand and pull production are critical.
>
> ... creating level pull production in an operation of any complexity is not easy. Even within Toyota it took 20 years of hard work and experiments, between 1953 and 1973, to establish the system companywide. A successful transformation requires the coordinated efforts of everyone in a facility looking at the needs of all the product-family value streams. This calls for system kaizen of material and information flow to support every value stream.

In lean manufacturing continuous flow is achieved by connecting material and information flow between processes. Kanban is the most usual tool for controlling information and regulating materials conveyance between production processes. Kanban coupled with takt time, flow processing, pull production, and level scheduling is what enables just-in-time* (JIT) production to be achieved in a value stream. Typically a kanban is used to signal when product is consumed by a downstream process. In the simplest case this event then generates a signal to replenish the product at the upstream process.

There are four major purposes for kanban [Smalley(2004)] :

- Prevent overproduction (and overconveyance) of material between production processes.

- Provide specific production instructions between processes based upon replenishment principles. Kanban achieves this by governing both the timing of material movement and the quantity of material conveyed.

- Serve as a visual control tool for production supervisors to determine whether production is ahead or behind schedule. A quick look at the devices that hold kanban in the system (kanban accumulation posts) will show if material and information are flowing in timely accordance to plan or if abnormalities have occurred.

- Establish a tool for continuous improvement. Each kanban represents a container of inventory in the value stream. Over time, the planned reduction of the number of kanban in a system equates directly to a reduction in inventory and a proportional decrease in lead time to the customer.

The signal kanban is used to convey make instructions for large quantities to upstream batch processes such as stamping presses and molding machines. It utilizes batch boards in conjunction with inventory markets. Each item in the market has a kanban that is detached and returned to the upstream producing process as inventory is consumed. Once the kanban cards accumulate to an established amount (trigger point), replenishment begins in accordance with the number of cards. This form of signal kanban differs from an in-process kanban in that cards are grouped into a production lot, rather than production occurring one card at a time.

Another form of signal kanban is known as the triangle kanban. Triangle kanbans are used to schedule a batch process that has substantial changeover times and machine cycle time significantly faster than the takt time of production downstream. This kanban uses a lot size for production in conjunction with a trigger point to replenish inventory and is frequently used for stamping, injection molding, and similar processes. A key benefit of the triangle kanban is that only one kanban per part number is created - multiple cards do not need to be managed.

* Just-in-Time (JIT) is an inventory strategy implemented to improve the return on investment of a business by reducing in-process inventory and its associated carrying costs.

2.4 Heijunka

Manufacturing facilities are constrained due to machine capacity requirements, technical requirements of machinery and limitations in human resources. They cannot be equipped to handle the peak requirements at all times as this would create idling time in off-peak periods. This is a cost and non value adding from the customer's point of view.

Production leveling is an important aspect of lean manufacturing and is called Heijunka in lean context. Heijunka is any mechanism that prevents machinery and labor overload in the peak seasons and guarantees a minimum utilization in the less demanding seasons by leveling out production loads. Traditional approaches try to level production in volume (similar volume for different periods of time) and mix (similar mix in different periods of time).

From a high level perspective, Heijunka seems to create a conflict with JIT, as it can create some additional finished goods inventory (FGI) in the system and depends on predictions rather than actual demand. Nevertheless, it is integrated as part of lean manufacturing as it reduces the cost of operation and the stress on employees and machinery.

2.4.1 Heijunka board

The standard tool in Toyota Production System to introduce leveled schedules in manufacturing environments is Heijunka boards, which are described by [Furmans(2005)] in the following quote:

> The system described in figure 2.1 works as follows: The customer requests parts in regular intervals, possibly with kanban cards. The requested parts are taken from a finished goods inventory (often called "supermarket") and are shipped to the customer. The same number of kanban cards (usually one per shipped container with finished goods) is sorted into the heijunka board. According to the number of parts which should be produced in every base period, spaces for kanban cards of the respective product are reserved in the heijunka board. If more kanban cards are generated due to higher demand, the excessive cards are stored in an overflow location. If not all spaces for the kanban cards for a specific products can be filled, cards from the overflow location are added, if they are referring to the same finished product. Allocated space which can not be filled stays empty in order to avoid producing goods which are not requested.

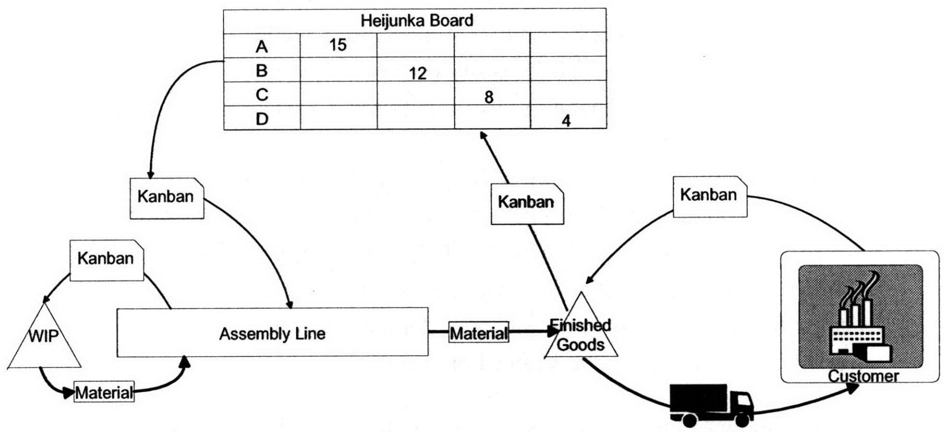

Figure 2.1: Heijunka systems. From [Furmans,(2005)]

2.5 Push systems

Push systems are centralized schedule generation systems that coordinate processes so that all departments can work at the same cadence. They are usually represented by IT solutions such as Materials Requirements Planning (MRP) systems. Traditional implementations of these systems are updated once a day and provide expected production schedules for all production groups for the following seven or twenty eight days.

2.5.1 Lean perspective on Push systems

A typical criticism by lean thinkers [Smalley(2004)] of these systems is that, in reality, they cannot adapt to the complexity of the shop floor:

> Problems inevitably enter into the equation when assumptions for lead time, scrap and yield rates and other inputs are wrong. The shop floor is a dynamic place. It changes minute by minute throughout the day while MRP systems typically work with a time fence of anywhere from a shift to a week. The MRP needs to be continuously updated about the actual status of production on the floor, but this is difficult to achieve. Often schedules, production status, and inventory levels are only updated overnight in a batch program, making them useless for resolving problems arising throughout the day. For all these reasons, the most advanced software systems poorly execute real-time, shop-floor control for production between processes.

Lean literature recommends the use of pull-systems for real time scheduling but doesn't dismiss the need for planning systems based on IT tools such as MRP for other means such as purchasing. Daily or weekly production plans still need to be generated in manufacturing environments for a variety of reasons:

- The production and inventory management systems of deteriorating items (e.g. medicines, volatile liquids, food stuffs, etc.) are most common in reality. [Giri(2003), Giri & Moon(2004), Moon(2002)] show that there are significant benefits of studying the size of finished goods inventory in deteriorating items with time varying demand, finite production rate and shortages over a known planning horizon.

- In the chemical batch processing industry, scheduling is a very important problem given the inherent in flexibility of the plant. It involves the determination of the order in which different tasks are carried out on different equipment and the detailed timing of the execution of all tasks so as to optimize plant operation in terms of some specific performance criterion. [Vin & Ierapetritou(2000), Lin(2004)] are examples of the research in this area.

- Assembly lines where more than one model is assembled simultaneously are no longer a novelty in the world automobile industry. However, Honda's system for mixing models on the line differs from Toyota's better known variant. [Mair(1998)] reports employee savings due to Honda's batch-based policy. Such a policy would lead to potential savings in labor requirements due to line workload differences among different models. Often, on both sides of optimum inventory level large changes in lot size bring minuscule changes in inventory cost. This indicates that there is a range of realistic lot sizes that would minimize the inventory and labor cost. Several authors [Young(1967), Pinto(1983), Chakravarty & Shtub(1985)] have studied batch-based schedules in multi-model assembly lines.

2.5.2 The Stochastic Lot Scheduling Problem

Scheduling production of multiple products on a single facility that incurs significant change-over costs or times is one of the classic problems in production planning research. Multiple reviews of the literature on this problem can be found on [Graves(1981), Sox(1999), Giri(2003)]. Applications include bottling, paper production, molding, and stamping operations. Any production process with significant change-overs between products benefits from an effective scheduling system.

Models can be classified according to time division. The first are continuous time models that developed into what has come to be known as the Economic Lot Scheduling Problem (ELSP). The second line of research includes the discrete time models that are often called the Capacitated Lot Sizing Problem (CLSP). [Elmaghraby(1978)] and [Davis(1990)] provide surveys of the ELSP. [Salomon(1991)] provides a review of the CLSP research. Both areas of research address lot sizing and sequencing questions based on the assumption that future demand for each product is deterministic. While this assumption is useful in some applications, there are many other applications in which the uncertainty of demand is a significant complicating factor.

A similar problem to that described in sections 1.3.1 and 1.3.4 is the Stochastic Lot Scheduling Problem (SLSP). This is the problem of scheduling production of multiple products, each with random demand, on a single facility that has limited production capacity and significant change-overs between products. The literature contains a wide range of quantitative techniques that have been applied to this problem. [Sox(1999)] classifies the periodic-review policies in the literature in two groups: dynamic sequencing and cyclic sequencing. The papers in the cyclic sequencing category use a fixed, predetermined cyclic sequence on the facility to determine the production sequence, and the lot sizes are varied to accomodate demand variation. Dynamic sequencing papers vary both the production sequence and lot sizes to accommodate demand variation. The papers by [Gallego(1990)] and [Bourland & Yano(1994)] use a cyclic sequence while the papers by [Graves(1980), Qiu & Loulou(1995), Vergin & Lee(1978), Leachman & Gascon(1988), Sox & Muckstadt(1997)] use dynamic sequencing.

According to [Sox(1999)]

> ....Inventory of each product serves three roles in this problem. First, through lot sizing, the inventory reduces the economic cost of performing change-overs, and reduces the fraction of production capacity consumed by change-overs. Second, the inventory for a product serves as a hedge or buyer against stockouts because of the variation of demand in the interval between production runs for that product. Third, the inventory of a product serves as a hedge against scheduling conflicts that result from the variation in demand for other products. This third role may also be accurately called safety stock, but it divers from the usual meaning of that term. It is the notion that the benefits of safety stock invested in one product can be shared among all the products.

Traditional approaches to this problem in practice fall into two broad categories: independent stochastic control and joint deterministic control. Independent stochastic control methods use an independent inventory control policy, (s, S) or (Q, r), for each product to determine the production lot sizes and release times. The production schedule is based on the current order releases possibly with some expediting of products that have critically low inventory levels or high backlogs. Lead times and safety stock levels are established based on past experience. This approach does not exploit the benefits of jointly controlling inventory levels and scheduling production simultaneously for all products.

The Carrier Job Problem The problem faced by the scheduler of the carrier job (see sections 1.3.1 and 1.3.4) has a similar nature to the SLSP. Unfortunately, there are two main differentiating features. First, supply and not demand is the main source of uncertainty. She doesn't know what the total number of units produced on that day is going to be. Second, supply is stochastic in its volume but not in its sequence. She might not know how many units are going to be built, but she knows how many units of the first type are needed before the first unit of the second type is built.

Under this scenario, inventory of each product has four functions: First, inventory for change-overs. Second, the inventory as a hedge for downtime in the downstream machine. Third, inventory as a hedge for upstream machine downtime. Fourth, inventory as a hedge against scheduling conflicts that result from the variation in demand or supply for other products.

Chapter 3

Level schedule

3.1 Introduction

This chapter describes a lean improvement initiative carried out at AAM Plant 2. The first section describes the context in which this initiative was carried out and the reasons that led the management team to believe in the need for this project. The second section describes the new system and some of the most inportant challenges faced in the implementation of this initiative. Finally, the last section describes some of the recommendations that the management team should consider going forward with this initiative.

3.2 Context

3.2.1 Results from previous lean initiatives

Historically, there had been several lean initiatives in the final assembly area. Many of them had failed due to lack of training in Lean principles among operators and managers. Recently, there had been some major successes that had achieved a major impact on the operations and increased lean credibility in the plant. Nevertheless, as of June 2006 there was still room for improvement in material flow and production stability in Plant 2 and many expected a major initiative to be taken in this direction.

For a variety of reasons, the final assembly line was usually forced to deviate from its schedule. This was an important issue as it forced to hold an important amount of capital in the finished goods inventory. In order to evaluate the trend of this effect a measure called 'build attainment'* was measured on a daily basis.

*Build attainment: ratio between the number of parts built according to schedule and the number of parts initially scheduled

The trend of this measure in the period between June and December of 2007 is graphed in figure 3.1. Note that, at the beginning of the study period, this measure was on the 60% level, i.e., only 60% of the parts requested were built.

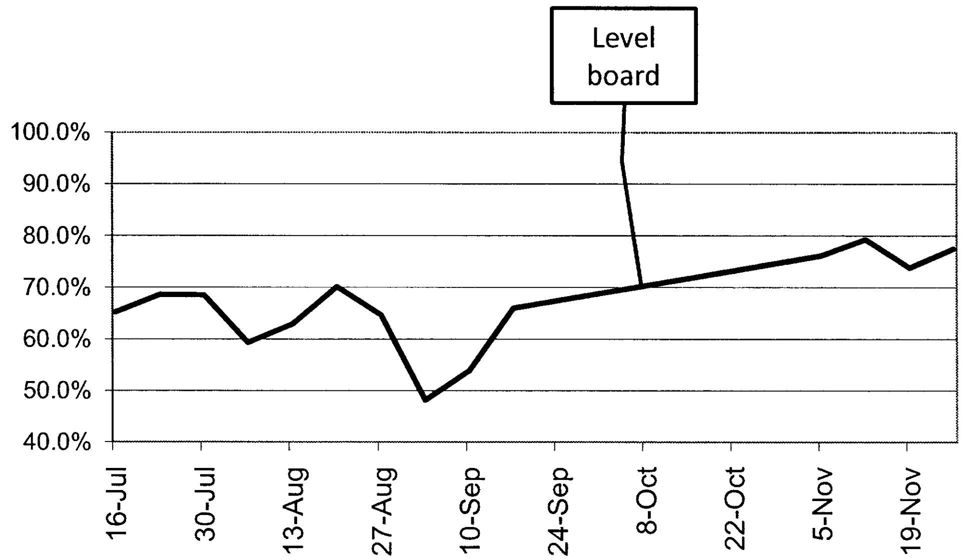

Figure 3.1: Build attainment trend

3.2.2 Inventory management system

The inventory management system in Plant 2 was mixed. Raw materials were managed under a sequential pull system, i.e. new orders were released when finished goods were delivered to the customer. Sub-assemblies were managed under a replenishment system, i.e., component groups had certain inventory levels that need to be replenished when material was demanded from the assembly line.

A material flow chart describing this inventory management policy is described in figure 3.2. Note that all components in the plant are supplied through supermarkets, i.e. storage locations where each inventory type can be refilled and requested at any time.

Group unstability One of the main reasons for schedule deviation in the final assembly line was downtime and long changeover times upstream. Machining and welding groups were unstable because they had a significant amount of downtime. Often, because components were not available, the assembly line was forced to deviate from its schedule and build whatever was available at the time, even if not needed. Chapter 3 describes a major change initiative in supplier group production management.

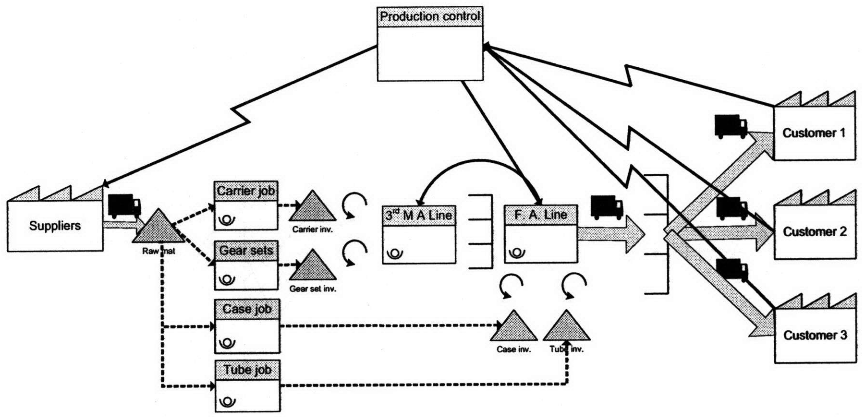

Figure 3.2: Initial material flow in Plant 2

Pacemaker and inter-assembly coordination As of June 2007, the pacemaker in this system was the final assembly line. All product lines were run on this line at least once a day and, on average, every shift. Change-overs could take up to 15 minutes but if effectively managed, they could effectively eliminated. Unfortunately, this was a difficult process to manage and supervisors preferred to postpone change-overs and order them for the breaks.

The system to coordinate final and third member lines was based on direct radio communication. Based on the one-day build goal provided by production control, final assembly line's supervisor decided the build schedule and sent WIP production orders to the third member line supervisor through a radio system.

Bullwhip effect An assembly line supervisor was often forced to deviate from the desired schedule and overproduce some products. This could be due to manpower, material unavailability or downtime in some operation. The recovery rate was low. Once a low-demand piece was missed on the schedule, it might not be built recovered until a few days later.

As a result of all these issues, even though the customer's demand was fairly stable, the final assembly line's demand communicated to all supplier groups varied daily. This phenomenon, called 'bullwhip effect', had significant influence on all the final assembly line's internal and external suppliers, which had to keep higher WIP inventories. Figure 3.3 compares the customer demand for the 12:41 gear sets with the daily production of 12:41 gear set axles for a period of one month. Note that the final assembly demand for 12:41 gear sets was more variable than the customer demand for axles with 12:41 gear sets.

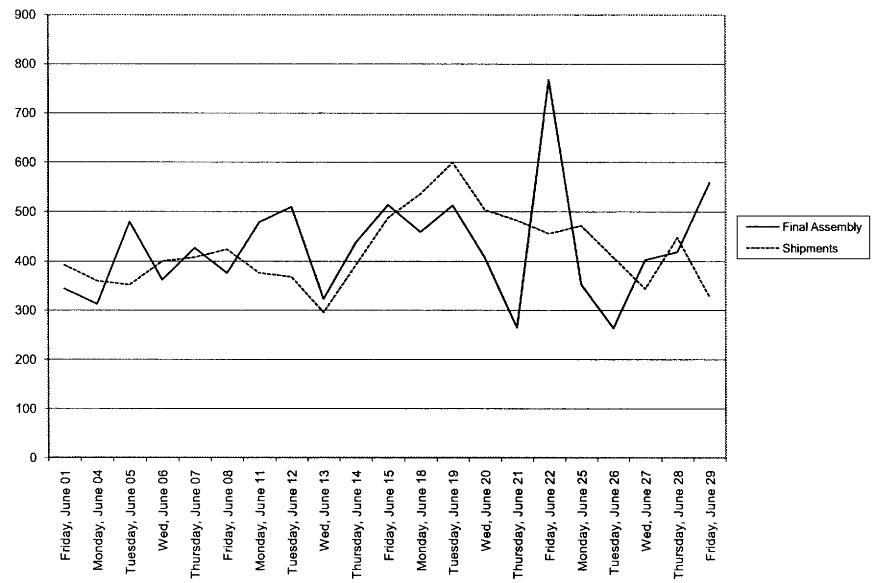

Figure 3.3: Bullwhip effect on 12:41 gear sets

3.2.3 Batch sizes

Batch sizes were a major problem too. Daily production needs came in multiples of 6 or 8, depending on the product and the customer whereas third member containers that served as input were in batches of 18 units. Therefore, when the customer demanded two batches of 8 units, a container of 18 had to be loaded on the line. The first 16 pieces were used to fill containers that could be shipped directly to the customer, but the remaining 2 units represented overproduction which had to be maintained in FGI until the next order came. This was a source of waste also because it forced the final assembly supervisor to have an operator at the end of the line loading partial racks. While this source of waste was obvious, it was hidden by other sources of partial racks such as First Time Quality (FTQ) †, or the fact that these racks were then shipped to an intermediary agent responsible for painting the axles and grouping partial in complete racks.

The third member line could not supply batches of smaller size than 96 pieces. This was due to the size of the gear-set standard packages, which only fork-lift drivers could handle. Whenever the third-member line needed to do a change-over, a different gear-set had to be loaded by a driver. Other components were supplied to the line in large batches but they were not an issue because operators could easily swap different models when necessary.

In order to adapt to the schedule in the final assembly line, third member

† First Time Quality (FTQ): average quotient between quality-accepted units over inspected units. Repairs of rejected units are ignored.

line managers had to follow a complex procedure. At the beginning of their shift they counted the amount of axles of each model that were available on the third member bank, compared them with the final assembly line schedule and noted the balance-to-build. Then, they created their own schedule, which would follow the final assembly line schedule with batches of larger size. This was a difficult task that only the most seasoned line managers were able to accomplish. New supervisors on the line would occasionally starve the final assembly line or force it to deviate from its schedule.

Third member line managers were not held accountable for the mix in the third member bank at the end of their shift. It was not difficult to find that, once the parts needed by the final assembly line had been requested, third member supervisors dedicated their capacity to a highly demanded model. This way they were able to maximize the number of parts built on their shift. Section 3.2.4 explains this behavior.

3.2.4 Incentive structure

Supervisors' incentive systems lead to incorrect behavior. Supervisor's perception was that their performance was mostly measured by productivity, but not build attainment. Since their goal was to assemble as many pieces as possible, their tendency was to reduce the amount of change-overs since they could only slow the line. This perception was enforced by a performance report that had to be filled at the end of every shift and by part of the senior management in the organization who only asked for productivity variables.

Cross-shift competition was enforced by the incentive systems. There was substantial competition between the managers in the same position in different shifts as their performance was constantly compared and the "stars" in each department were clearly visible.

3.2.5 Communication systems

Cross-shift communication The schedule was centralized on a single person: the outbound scheduler. The main responsibility of this position was to have an updated vision of what needed to be built for the following shift. This task involved comparing actual production with customer demand and posting balance-to-build for the following shift. This position was not supposed to be available at all times of the day.

This system had serious disadvantages. First, all the cross-shift coordination responsibility was put on a person who was not supposed to be available at all times of the day. In fact, 3rd shift never received an updated schedule with what the previous shift actually built. Second, this centralized system didn't allow the three shifts to work as a team as decisions taken by one of them were not visible to the others. Each shift worked blindfolded as nobody knew what was the cause of schedule deviations and there was no opportunity to evaluate decisions taken in other shifts.

Supplier group communication Communication by radio had disadvantages too. While it was fast and flexible, it didn't allow operators and fork-lift drivers understand how the decisions were taken and they could not forecast what was coming next. They were left "out of the loop". As a consequence, supervisors could not rely on them to run the schedule. Additionally it didn't provide cross-shift accountability as final assembly supervisors could not hold the third member supervisor of the previous shift accountable for the mix in the third member inventory at the start of their shift.

3.3 Heijunka board

In order to minimize the dependency on a single person responsible for updating the schedule, a Heijunka board (described in (2.4.1) was recommended. Heijunka is a key element of the Toyota Production System. It is used to level the release of production kanbans in order to achieve an even production program over all possible types of products thus reducing or eliminating the bullwhip effect. It levels the production of different products evenly over a defined period, which could be a day, a shift or less. The goal is to achieve a constant flow of parts in a mixed model production which supplies one or more customer processes with a constant flow of different parts. A constant demand of parts is generated for the upstream processes, thus reducing or eliminating the need for spare capacity or stocks to cope with peaks of demand.

3.3.1 System description

The Heijunka board in AAM Plant 2 (see figure 3.4) was updated once a day. The schedule was planned at the end of the week for the following week and it had to be robust so that it could be repeated every day of the week. Everyday, approximately at the end of first shift, the outbound scheduler would update the cards on the board with the schedule for the following three shifts. On the board there was a column for every hour in a 24 hour period. Every column contained a set of cards, each corresponding to a third member container. Every time a fork-lift driver loaded a container of third members on the line he reported it by flipping the corresponding card on the board.

If a card was not flipped within its shift (and the corresponding group of axles was not built), it was left in its position to let the following shift recover it. The priority of each supervisor was to build what had been programmed on their shift and, if possible, recover missed parts in previous shifts.

As a result the schedule set on the board dictated the sequence by which containers had to be loaded on the line and schedulers obtained real time feedback of which parts of the sequence were not actually followed. If a card was not recovered within the 24 hour period, the outbound scheduler would put it in a separate area of the board dedicated to these cards called "missed" area, which was updated every week.

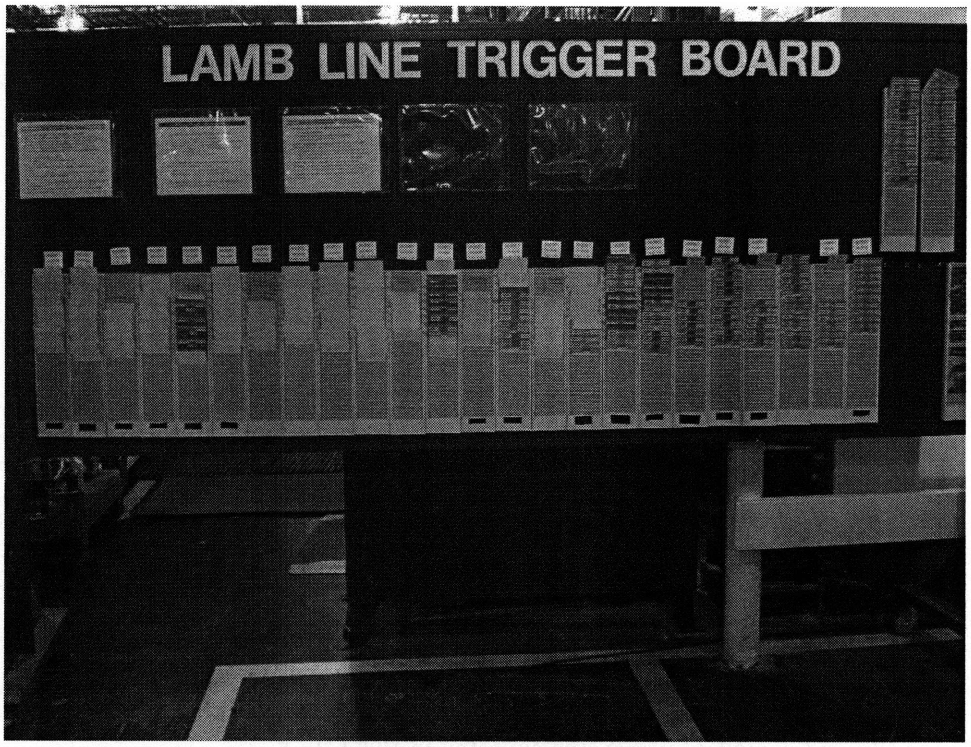

Figure 3.4: Heijunka board at AAM Plant 2

3.3.2 Immediate benefits

Overall, the heijunka board had a significant impact in AAM Plant 2. While it was initially considered a source of unnecessary complication for many of the workers and managers, it was soon accepted as a means for coordination. Several immediate benefits were identified:

1. The schedule was accessible to operators and managers. Fork-lift drivers were empowered with the responsibility to call a change-over so that managers could concentrate their efforts in quality issues. Employees with special responsibility on change-overs could forecast when they were going to be needed on the line.

2. Cross shift communication was simplified. Managers no longer had to provide each other with a list of the parts they missed. Parts missed in previous shifts were easily detectable on the board managers, which could then adjust their schedule to recover these parts. Changes in the schedule in one shift were visible to the other shifts and managers were accountable for them.

3. Since the schedule was the same across the week, operators and managers were able to memorize it. This saved time, improved quality and helped to correct errors on the line.

4. The Heijunka board became the source of truth. The schedule, as described by the heijunka was the reference for workers and managers. No longer did they look at their paperwork to find the 'expected' schedule, as opposed to the 'real' schedule.

3.3.3 Stakeholders

Due to repeated failures in the past, there was a significant skepticism in the plant towards Heijunka systems in particular and lean in general. Fortunately, recent successes in other lean initiatives had gained credibility, which was necessary to keep stakeholders' involvement. These had different views on the project:

Project leadership was provided by the manufacturing manager of the entire site, Detroit Gear & Axle (DGA) and the Lean Deployment Group. The Heijunka system had been a successful transformation experience in other plants within the site and a similar success was expected in Plant 2.

Materials department. In the past, materials department had successfully led the implementation of similar systems in other less complicated plants but they lacked a knowledgeable figure in the plant. The outbound scheduler, a representative of the materials department, had recently been replaced and the new one was less knowledgeable about manufacturing constraints in Plant 2.

Production supervisors as the inheritors of this system, were the main stakeholders in this project. Prior to the implementation of a Heijunka board, supervisors of the final assembly line were told the number of axles of each type they needed to have by the end of the day. They were not restricted by shift or sequence production. Therefore, this initiative was a significant limit to the flexibility they were used to on their operations. Their initial resistance disappeared once the plant manager unmistakably supported this initiative.

The Union as representatives of the hourly workers, were also an important stakeholder in this initiative. UAW representatives received complaints from fork-lift drivers that this system represented additional workload for them. This issue was risen to a formal complaint where the team was requested to show a time study of the jobs which would be influenced by this initiative. Again, once the fork-lift drivers were trained and saw how this system would help their day to day life, these issues were solved.

3.3.4 Performance measures

The first step in this initiative was the establishment of new performance measures. Traditionally, supervisors performance was calculated as productivity at the end of their shift. Sequence attainment[‡] was established as a new performance measure that was calculated by the outbound scheduler and notified to the plant manager. It was posted by the end of the day so that the plant manager could go over it in his daily meeting.

The new performance measure had immediate resistance by some of the production managers, who were used to choose productivity over build attainment whenever there was a conflict. For example, change-overs were usually scheduled on the breaks in order to minimize assembly line down-time. This strategy was good as long as materials requirements for each axle family could be fit in the corresponding period, but whenever this wasn't the case and they had to choose between build attainment and productivity, they usually opted for the latter.

Another element of dissension was day-to-day measurement, which represented a credibility burnout for the new system. In some cases, due to customer needs or any other exceptional situation in the supply chain, the schedule had to be modified. The measurement system did not capture these special circumstances and compared actual build with the deprecated schedule. As a consequence, build attainment results decreased and the credibility of the new measure was put to question.

3.3.5 Multiple batch sizes

Among different models

As section 3.2.3 describes, standard delivery packages had different sizes depending on the final customer. Therefore, kanban cards for these packages had different sizes depending on the model (some in batches of 18 and some in batches of 16). In order to minimize partial packages, the containers of third members had to leave two empty slots for some models.

While this change wasn't a great effort for the unloading operator, who started to execute the order as soon as he was explained, it did create dissension among

[‡]Number of parts built divided by number of parts demanded for each product

managers. Some considered that it would increase the factory floor required to store the third member inventory in front of the assembly line. They also argued that there wouldn't be a reduction of partial containers generated since FTQ was so high in the third member assembly line.

Among different lines

The most difficult element in the implementation of a Heijunka system in AAM Plant 2 was the existence of different batch sizes in the lines (see figure 3.5). As section 3.2.3 describes, gear sets were delivered in batches of 96 units to the third member line and these standard packages could only be handled by fork-lift drivers. As a result, the third member line could only be efficiently managed with batches of 96 or, exceptionally, 48 units. Since the final assembly line dealt with batches of 16 or 18 units, material flow between these lines was a significant issue.

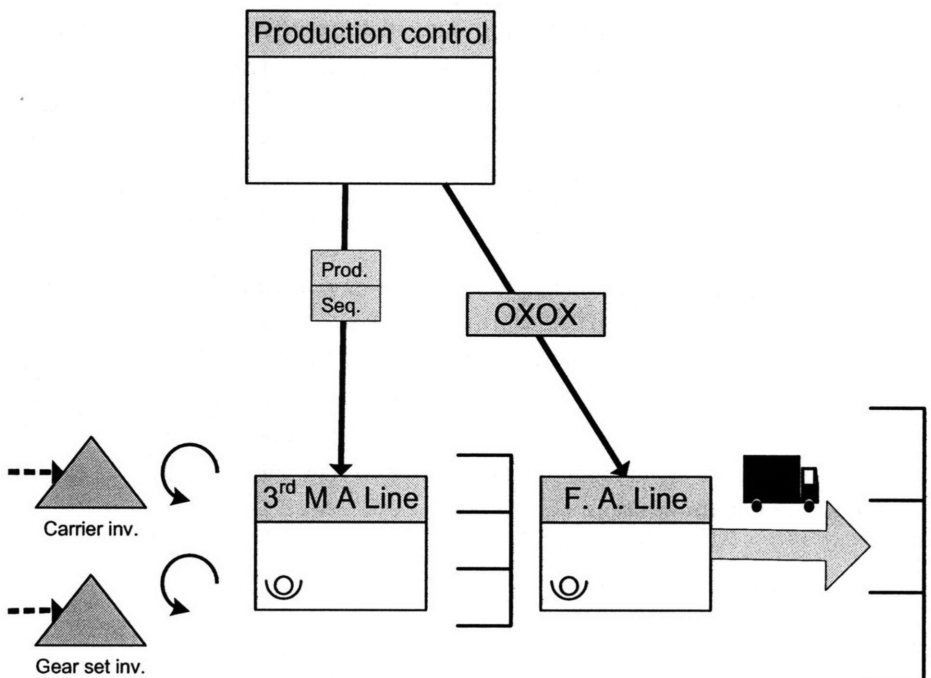

Figure 3.5: Material flow once the heijunka board was installed

In order to solve this, it was decided to make third member and final assembly lines run unconnected schedules which would be sent to them by the outbound scheduler. The inventory of finished third members (third member bank) was supposed to keep approximately one shifts' worth of demand. The goal was to make the final assembly line assemble the parts that had been built on the previous shift.

This system was problematic as it was very dependent on the third member bank, which varied widely along the week. As soon as the desired parts were not found on the bank, a manager in the final assembly line called the third member line to make sure that the following batch was of the desired type. This forced the schedule in the third member line to adapt to new demands from the final assembly line, ignore the schedule provided by the centralized system and follow the traditional system described in section 3.2.3.

The green cards system

In order to increase the communication between third member and final assembly line across different shifts the team that the author was part of implemented a new system. Whenever a new container of third members was delivered from the third member area, it had to be reported on the Heijunka board by putting a green third-member-ready card behind the corresponding final assembly card. Once a card was flipped, the corresponding third-member-ready card was taken out of the board. The result was that the green cards provided a visual representation the state of the third member bank and how close it was following the final assembly line's schedule.

This system had significant benefits: third member line supervisors had a visual system to validate their schedule, final assembly line supervisors could hold the previous shift accountable if the bank didn't fit with their sequence, and operators and fork-lift drivers were aware of the causes for a deviation and could foresee it. More importantly, this system increased the awareness of this problem among all stakeholders.

3.4 Recommendations for future development

3.4.1 Pace-maker position

While it is natural to set the pace-maker process on the last operation in the plant, the final assembly line, managers at Plant 2 might want to consider positioning it in the third member line and setting a FIFO material system between third member and final assembly line as described by figure 3.6.

If the schedule was set on a Heijunka board that coordinated the schedule on the third member lines, the supervisors would be able to rely on their operators to run the schedule and concentrate on quality and discipline issues. A similar situation would arise in the final assembly line, where the schedule would be dictated by a FIFO system.

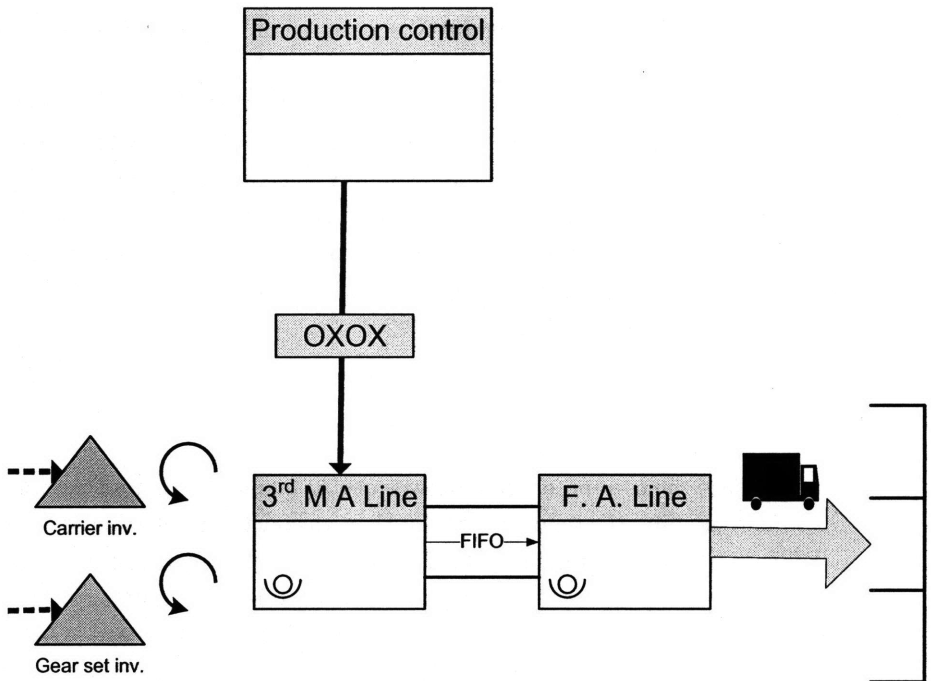

Figure 3.6: Heijunka board on the third member lines

Batch sizes

The key change to make this system work is batch sizes. As section 3.2.3 describes, there are different batch sizes in third member and final assembly lines and the FIFO system cannot connect processes of different sizes. Two options could be considered here:

- Batch sizes of 96 units in both lines. This solution would lead to larger finished goods inventory as this amount could represent the demand of three or four weeks for the least demanded products. On the other hand, it has the benefit that no initial investment needs to be established.

- Batch sizes of 16-18 units in both lines. This solution implies the investment in new gear-set containers which can be easily handled by operators whenever there is a change-over on the third member line.

Coordination

Another element to be considered is the difference in capacity between third member and final assembly groups. While the former runs two different lines with two shifts each, the latter runs only one line with three shifts. In order to coordinate material flow, one third member line (NW), the one closest to the final assembly line (LL) in the floor layout, would need to run three shifts and the other line would run only one shift for support on the high runners, as figure 3.7 shows.

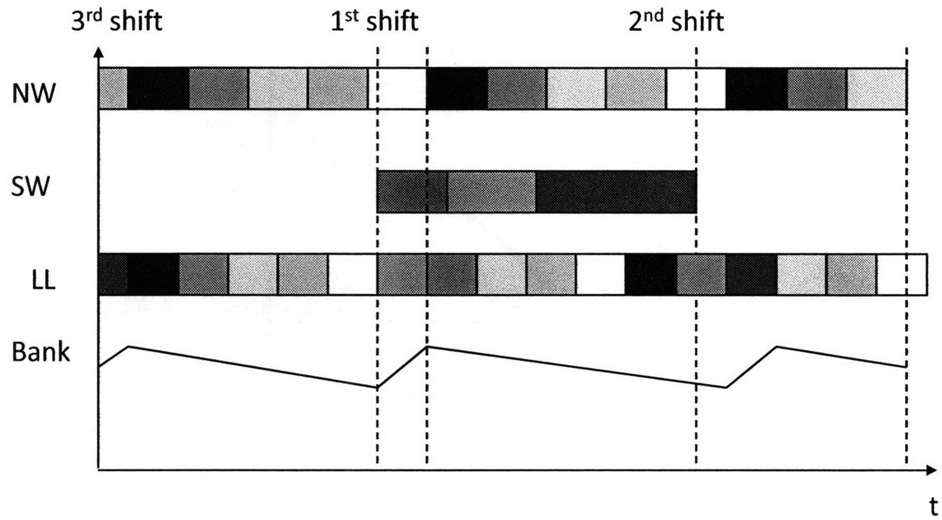

Figure 3.7: FIFO lanes coordination

3.4.2 Finished Goods Inventory

Finished goods inventory is stored at a third party's warehouse once it is painted. While this operation might seem a minor part of the value chain and the decision to out-source it had been right in the past, the vision shared by all stakeholders was that it had to be brought in again. This action would have major benefits, among them, it would facilitate an immediate feedback system between changes in finished goods inventory and updates in the production schedule.

3.5 Results

The impact of this initiative in plant 2's operations is represented by three elements: reduction in finished goods inventory, reduction in WIP inventory, reduction in supervisor hours dedicated to scheduling and operator moral improvement.

Due to reduced demand variability in automotive industry, finished goods inventory in AAM plant 2 is almost completely dictated by build attainment, which was improved by 20% according to figure 3.1. The corresponding capital release has been estimated to amount up to $1M with the corresponding interest rate savings that range between $130K and $180K. Unfortunately, this figure

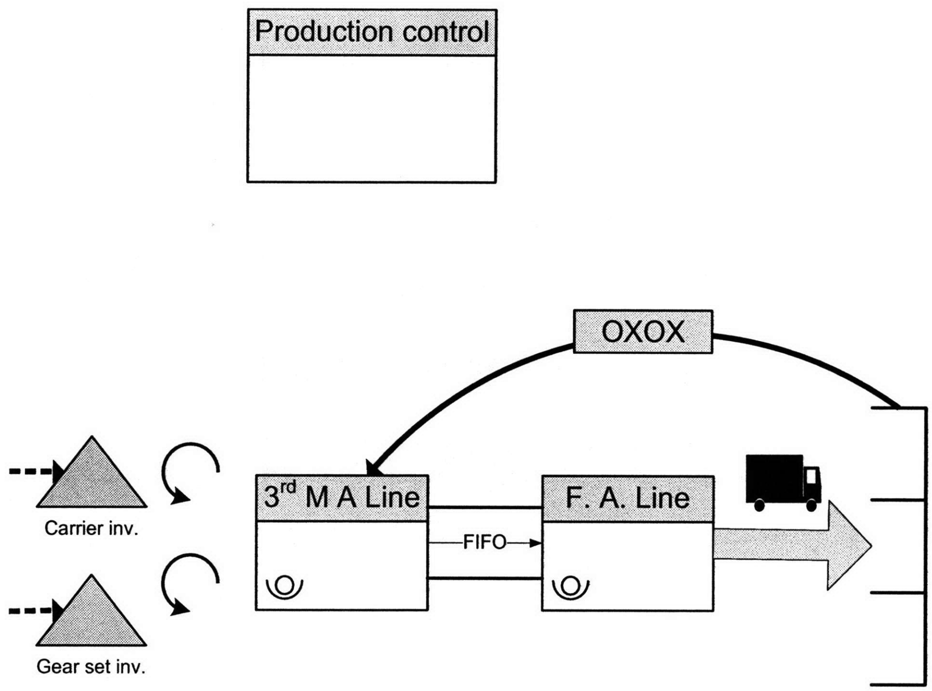

Figure 3.8: Finished Goods Inventory in house

which only resembles results achieved until December 2007, but better build attainment results have been achieved after this period.

WIP reduction as a result of material flow was not measured as it still had not been achieved by December 2007.

Supervisors who relied the scheduling function on their operators and the Heijunka system reported approximately that, on average, one hour of the time they dedicated to scheduling issues was now dedicated to quality control. This has been estimated to represent approximately $50K due to repairs and material savings.

Total, this project has resulted in a minimum savings for the company of $180K. Operator and supervisor moral cannot be measured in $ but should also be taken into account.

3.6 Conclusion

This chapter has described a lean initiative that took place in the assembly area of AAM Plant 2 between June 2007 and December 2007. The first section of this chapter describes the state of the system at the time when this initiative took place. The second section provides a description of how the Heijunka system was implemented and some of the major challenges faced by the management team. The third section some recommendations that the management team might want to consider going forward with this initiative. A final section with estimated economic returns of the development of this system is also provided.

While this chapter describes some of the major challenges faced in the final assembly area it doesn't provide an insight into the machining and welding areas, which are responsible for a large amount of the unstability in this plant. The following chapter provides a more thorough description of this area and some of the improvements carried out during the June 2007-December 2007 period.

Chapter 4

Work in process management policy

As it can be observed in figure 1.2, material management in plant 2 is complex. There are multiple parts inventories that need to be coordinated. Multiple processes and operations, some of which are very unstable. Multiple internal customers for some of the sub-assemblies which expect compliance with delivery times. Most importantly, the final assembly line is running approximately 4,000 axles every day.

For all these reasons, the material flow and material requirements communication between processes must be flawless. As of June 2007, the inventory of components and subassemblies was scheduled once per day based on a snapshot of inventory levels. Every day, at the start of first shift, the component groups' supervisor would re-assign capacity to each component based on the work-in-process (WIP) levels at that moment. This was not an easy task since variability of both, component groups' production and final assembly line demand had to be taken into account.

While this procedure proved to be successful for all other groups, two processes were traditionally pointed out as the source of most deviations in the assembly line: the tube job, and the carrier job.

This chapter describes the material management policy for these two processes and how it was improved by some of the techniques described in chapter 2. First section concentrates on the tube job. Second section concentrates on the carrier job and provides an analytic formalization of this problem. Third and fourth sections describe and provide a case study of a visual tool that can be used to solve the problem described in section 2.

4.1 The tube job

4.1.1 Context

Figure 4.1 shows the process the tubes follow from the time they enter in the system until they are sent to the corresponding assembly line. As it can be observed, the tube job in Plant 2 supplies tubes to two different assembly lines: plant 2's assembly line (LL) and another internal customer called plant 3. The gray inventory symbols correspond to tubes demanded by LL while the white ones correspond to the tubes demanded by plant 3.

The tube job carries out the tube machining and welding operation for three axle families: G-9V, G-9NV's and G-10. The tube machining and welding for G-6 axle family is out-sourced.

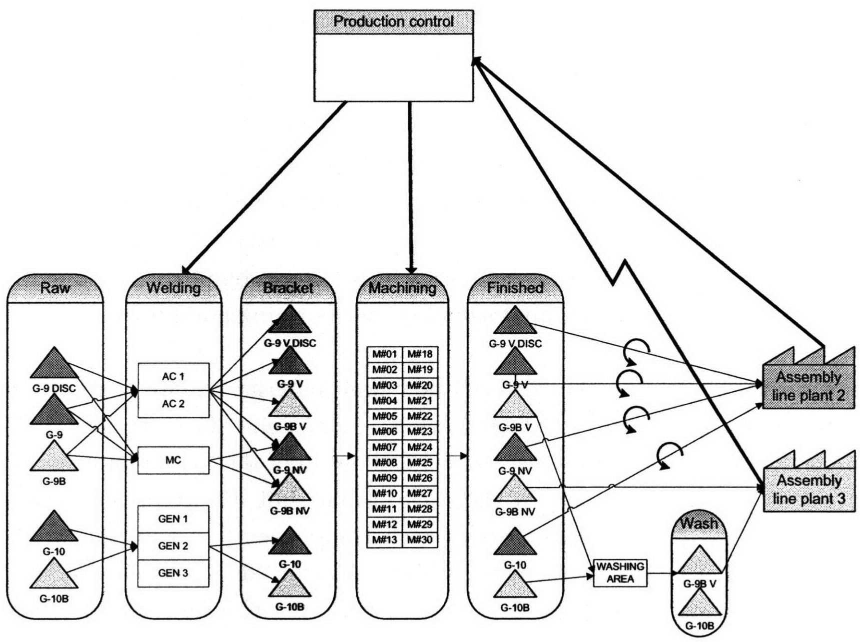

Figure 4.1: Tube job material flow

As it can be observed in fig. 4.1, the welding area is comprised of six different machines. Three of them, called GEN, are dedicated to G-10 family and the other three, the AC-1, AC-2 and MC, are dedicated to the G-9 family. The MC is usually dedicated to G-9 NV tubes whereas the AC-1 and AC-2 alternate among the G-9 V and NV families. Setup times of approximately 20 mins have to be respected for change-overs in AC-1 and AC-2. Similarly, the GEN machines alternate among all the G-10 tubes.

The machining area is comprised of thirty different machines. These machines have long setup times (approximately 4-5 h) when they alternate between G-9 and G-10 families but shorter ones among tubes in the same family.

It is difficult to plan welding and machining capacity. Demand and production rates for each product are uncertain, there is high diversity in demand across products, materials requirements are inefficiently communicated across plants and, most importantly, multiple operations and part inventories to manage.

As of June 2007, capacity planning for this operation was done by a supervisor who, in addition to this task, was responsible for quality and labor management. A typical strategy was to assign capacity proportionally to weekly demand and react if any individual inventory level in front of the final assembly line dropped too low. The tube job was usually pointed out as the source of most deviations in the final assembly lines of Plant 2 and 3. While some of these deviations were due to unscheduled downtime in the machines, many were due to inefficient communication of materials requirement across the different processes.

4.1.2 Signal kanban systems

In order to solve all these issues, a kanban signal system similar to those described in section 2.3 was implemented. In this system, each tube type has a bar code that can be scanned to generate production kanbans as inventory is consumed. Once kanbans accumulate up to an established amount (trigger point), a replenishment batch begins. This IT-based version of the signal kanban system solves one of the largest difficulties in the process: materials requirements communication with plant 3 assembly line.

Figure 4.2 provides a diagram of the kanban-based material flow policy. Note that a series of interconnected kanban systems could have communicated the welding operation with the inventory in front of the machining operation and the machining operation with the inventory in front of final assembly line. Instead, it was found best to send final assembly material requirements signals to the welding operation as it simplified the process and reduced the lead time.

One of the major decisions in kanban signal systems' design is the size of the loops, i.e., the number of kanbans for each product which determine the WIP in the system. They are determined by the formulas of inventory periodic review policy shown in equation 4.1.

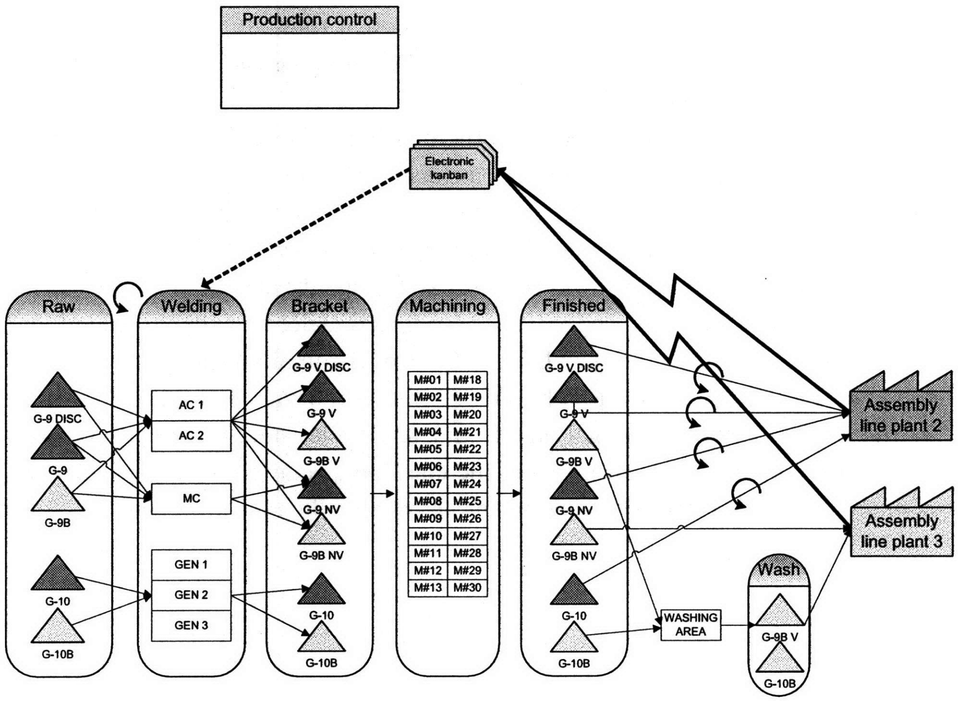

Figure 4.2: Signal kanban system

$$
\begin{aligned}
&\text{Parameters}\\
&l: \text{ lead time (days)}\\
&d_q: \text{ demand of product } q \text{ (units/day)}\\
&sm: \text{ safety multiplier}\\
&\text{Variables}\\
&cs_q: \text{ cycle WIP (units)}\\
&ss_q: \text{ safety WIP (units)}\\
&ts: \text{ total WIP}\\
&\text{Equations}\\
&cs_q = l \cdot d_q\\
&ss_q = cs_q \cdot sm\\
&ts_q = cs_q + ss_q = l \cdot d_q(1 + sm)
\end{aligned}
\tag{4.1}
$$

Note that variance in the demand during the lead time is not available. Instead, as [Smalley(2004)] recommends, a multiplier of the cycle stock has been used. Table 4.1 shows the application of these equations to the design of the system. Numbers have been modified in accordance to the disclosure agreement signed with AAM.

q	Std. Pack	d_q	lt_q (days)	cs_q (units & kanban)		ss_q (units & kanban)		ts_q	Trigger point
G-9 V D	36	45	5	225	6	68	2	9	7
G-9 V	36	1200	1	1200	33	360	10	43	10
G-9B V	16	85	5	425	27	128	8	35	29
G-9 NV	36	1300	1	1300	36	390	11	47	11
G-9B NV	16	9	5	45	3	14	1	4	4
G-10	16	48	2	96	6	29	1	7	4
G-10B	18	1100	1	1100	61	330	19	80	19
Total		2542		2966	133	890	40	175	67

Table 4.1: Tube kanban system size

Note that the difference in lead time for products that share the same process may be significantly different. This is due to the tendency of the system to give preference to high volume over low volume products. While this may be a good assumption when the process is launched, it should be expected that this time is reduced as operators and supervisors get used to the new system.

4.1.3 Implementation

As in other cases, several initiatives to implement a kanban system for the tube job had failed in the past. The implementation team identified three main several reasons for these failures: kanban system understanding among operators, efficiency in requirements communication and leadership support.

All the operators needed to understand the system to make it work. This was an issue as operators in plant 2 had very little experience lean or kanban systems and low motivation to learn them, since "lean" had been associated to head-count reduction. It wasn't clear to them what the benefits of lean were and they associated kanban systems with past failures.

Production requirements provided by the Plant 3 assembly line were not efficiently communicated due to the distance. Under previous designs cards were transported physically and this responsibility was difficult to track, as it was spread among too many people.

Finally, previous initiatives had not received the proper support from plant managers and general foremen, which were responsible for coordination of efforts among groups. Their support and excitement for any initiative in the plant was necessary as they were expected to hold operators to their responsibilities.

The first two issues were solved by means of a scanning gun, which eliminated the need for card transportation and the need for training multiple operators. Additionally, scanning guns had successfully been used in other initiatives in the

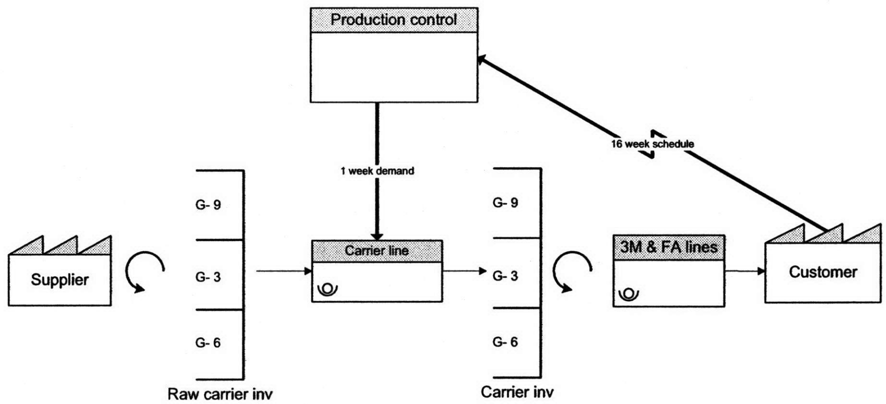

Figure 4.3: Carrier job material flow

plant, which attracted more perceived likelihood of success among operators and supervisors.

Leadership involvement was guaranteed in this initiative due to the personal involvement of the plant manager and the general expectation among upper management that Plant 2 would stabilize its assembly process.

Unfortunately, the tube job initiative was not launched until January 2008 and the author does not have any results about its impact on the plant.

4.2 The Carrier Job Scheduling Problem

4.2.1 Context

The carrier job is comprised of three machining groups which alternate between G-9, G-6 and G-3 carrier families. A material flow diagram for the carriers demanded in Plant 2 is shown in figure 4.3.

Change-overs take long in these groups. They don't have enough capacity to supply the assembly line during their regular schedule and need to run overtime. Overtime is expensive, much more than the cost of additional inventory, and for this reason managers try to minimize the number of setups by having a weekly cycle, i.e., all the product types are built at least, once a week. The weekly demand for G-3, G-6 and G-9 carriers is scheduled sequentially.

Figure 4.4 shows the carrier inventory level throughout six and a half consecutive weeks. The day of the week in each week is indicated by the corresponding number (1-5). As it can be observed, carrier inventory is mostly dedicated to G-9 carriers, which are the most demanded ones. Starting on Monday July 16, all capacity is dedicated to G-6 (note that this is the only inventory type that increases during that day), it changes to G-3 carriers on Tuesday (note that the G-3 inventory level increases that day) and concentrates on G-9 carriers during the rest of the week (G-9 inventory decreases by a lower amount during those days) but increases on the weekends (only the inventory next Monday is visible). A similar pattern happens on the following weeks. Note too that some weeks G-6 carriers are run earlier than the G-3's because they are needed earlier.

Note also that inventory levels are usually higher at the start of the week and that they drop at the end of the week. This is specially true for the G-9 carriers. The carrier lines have lower capacity than the final assembly line and, for this reason, they need to run overtime during the weekends in order to prevent starving it.

Another important element to be considered is downtime. Usually, G-9 inventory is only replenished during the weekends. Only when there is a significant amount of downtime on the final assembly line or when it deviates from the schedule does the slope of G-9 inventory level actually increase. The week of July 30 is an excellent example: as it can be observed, G-9 inventory increases by the end of the week because the S Carrier line was assigned to this model and the final assembly had a significant amount of downtime.

A similar situation arises on the week of August 20: G-3 carrier type is scheduled at the start of the week, but due to a failure on the line, the final inventory level is not enough for the whole week and a new changeover needs to be scheduled on the line by Thursday.

This section studies the decision faced by a scheduler of the carrier job, i.e., finding the best time for changeovers to take place in order to guarantee that the

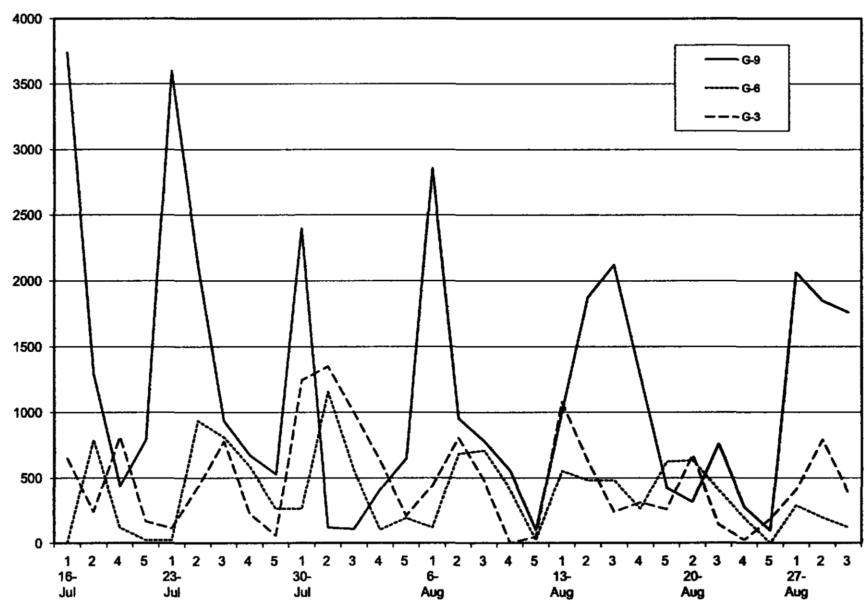

Figure 4.4: Historical inventory level

assembly line is not starved at any point in time.

The decision of when to carry out change-overs is done based on real-time production levels, i.e., the supervisors wait until a certain number of parts have been done before carrying out a changeover. As in the tube job welding area, if the carrier line dedicates too much time to the production of one carrier type and lets the other inventory levels drop too low, it might starve the final assembly line. The main difference between this operation and the tube job is that changeovers on the line take much longer and there is only one line that can carry them out. If a trigger board system was used in this case, there might be scenarios where two change-overs are triggered in a short period of time and one of them had to be delayed, which would potentially starve the assembly line. For this reason, it is necessary to think 'systematically' about changeovers on this line.

4.2.2 Analytic formulation

Assume the assembly line (product demand) produces each shift a normally distributed amount with an expected value μ_d and standard deviation σ_d. Its schedule is based on N_d batches of different size. All units in the interval (δ_{y-1},δ_y) $y \in (1, ..., N_d)$ belong to the same batch and demand the same type of carrier $q_d(y) \in Q$, where Q represents all the different types of carriers.

Similarly, assume the assembly line (product supply) produces each shift a normally distributed amount with an expected value μ_s and standard deviation σ_s. Its schedule is based on N_s batches of different size. All units in the interval (θ_{z-1},θ_z) $z \in (1, ..., N_s)$ belong to the same batch and demand the same type of carrier $q_s(z) \in Q$, where Q represents all the different types of carriers.

Indexes

$y \in (1, \ldots, N_d)$: sequence on the assembly line

$y(D)$: Batch corresponding to total demand D

$z \in (1, \ldots, N_s)$: sequence on the carrier line

$z(S)$: Batch corresponding to total supply S

$q \in Q$: carrier types

Parameters

μ_d, σ_d : Average and standard deviation of demand per shift

μ_s, σ_s : Average and standard deviation of production per shift

$q_d(y) \in Q$: Demand batch y is of type $q_d(y)$

$q_s(z) \in Q$: Demand batch z is of type $q_s(z)$

δ_y : Total demand by changeover y

θ_z : Total production by changeover z

The total production an assembly line produces each shift depends on the time to failure and time to repair of each different machine in the line. According to

Central Limit Theorem, under these conditions, production rates of the assembly line can assumed to be normal. Total production of both carrier and assembly lines after t shifts is the addition of total production in each shift and, therefore, a normal distribution with expected value equal to the sum of expected values per shift and variance equal to the sum of variances per shift.

$$\begin{aligned} D_t: &\quad \text{Cumulative demand by shift } t \\ &\quad \sim N\left(\mu_d \cdot t, \sigma_d\sqrt{t}\right) \\ S_t: &\quad \text{Cumulative production by shift } t \\ &\quad \sim N\left(\mu_s \cdot t, \sigma_s\sqrt{t}\right) \end{aligned} \tag{4.2}$$

Total demand of type q between time 0 and time t, $D_{t,q}$, depends on the total demand D_t and the sequence $(\delta_y, q_d(y); y \in (1, N_d))$. Similarly, the production of type q between time 0 and time t, $S_{t,q}$, depends on the total production S_t and the sequence $(\theta_z, q_s(z); z \in (1, N_s))$.

$$D_{t,q} = D_{t,q}(D_t, \delta_1, q_d(1), \cdots, \delta_y, q_d(y), \cdots, \delta_{N_d}, q_d(N_d)) \tag{4.3}$$

$$S_{t,q} = S_{t,q}(S_t, \theta_1, q_s(1), \cdots, \theta_z, q_s(z), \cdots, \theta_{N_s}, q_s(N_s)) \tag{4.4}$$

Let $I_{0,q}$ be the initial inventory of type q. The goal of the following formulation is to find the probability that the carrier line starves the assembly line at any time t, i.e., the probability that the inventory $I_{t,q}$, as defined in equation (4.5) is negative. As this equation shows, all the elements that need to be considered in this task can be grouped in two categories, random variables with known distribution, such as production and demand at any time (S_t, D_t) and deterministic parameters which need to be provided by the user, such as initial inventories, $I_{0,q}$ and sequences $(\delta_y, q_d(y), \theta_z, q_s(z))\forall y \in (1, \cdots, N_d), z \in (1, \cdots, N_s)$.

$$I_{t,q} = I_{0,q} + S_{t,q} - D_{t,q} \tag{4.5}$$

4.2.3 Random variables and the SD space

S_t and D_t, with density functions $f(S_t = s)$ and $f(D_t = d)$ respectively, can be assumed independent random variables as long as there is no starvation. If assumed independent, the joint probability density function (JPDF) is the product of the individual probability density functions.

$$f(S_t = s, D_t = d) = f_S(S_t = s) f_D(D_t = d)$$

Assume a environment with expected production per shift $s = 9$ units/shift and standard deviation $\sigma_s = 2$ units, expected demand per shift $d = 12$ units/shift units and standard deviation $\sigma_d = 3$ units. Accumulated production up to time t behaves as a normal distribution $S_t \sim N(9t, 2\sqrt{t})$. A similar situation happens

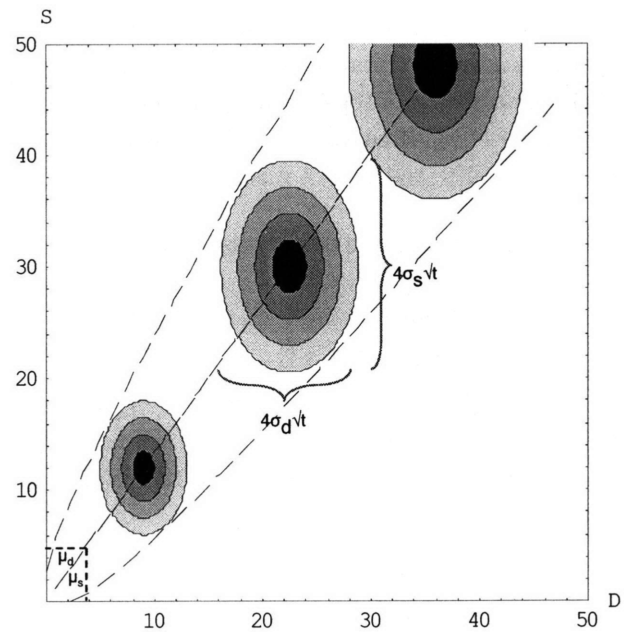

Figure 4.5: Locus of the points within two standard deviations of the expected value.

for accumulated demand up to time t $D_t \sim N(12t, 3\sqrt{t})$. Figure 4.5 shows the JPDF projection on a (S, D) plane for three different times $t = 1, 2.5$ and 4.

Note that the S_t, D_t joint probability density functions for different times are all aligned over a line that crosses the center of coordinates. This is the locus of all expected values, or expected values line (EVL), because the expected values of these distributions, $E[S_t]$ and $E[D_t]$, are proportional to t and, therefore, all the $(E[S_t], E[D_t])$ are aligned on a line in the SD space with slope $\frac{\mu_s}{\mu_d}$.

$$\frac{E[S_t]}{E[D_t]} = \frac{\mu_s t}{\mu_d t} = \frac{\mu_s}{\mu_d}$$

The distance from the center of the bell shape to the center of coordinates grows proportionally with time t. On the other hand, the width of the bell shape grows with the square root of time. The dashed lines in figure 4.5 show the locus of points in the (S, D) space within two standard deviations of the center of the bell shape. Any S_t, D_t combination below the lower dashed line has less than 98% chance of happening.

4.2.4 Deterministic variables and boundary lines

Given a schedule, the (S, D) plane can be divided in two regions for each inventory type q, the region where inventory is positive I_q^+ and the region where inventory is negative I_q^-. The following paragraphs show how the inventory positive and negative regions can be obtained.

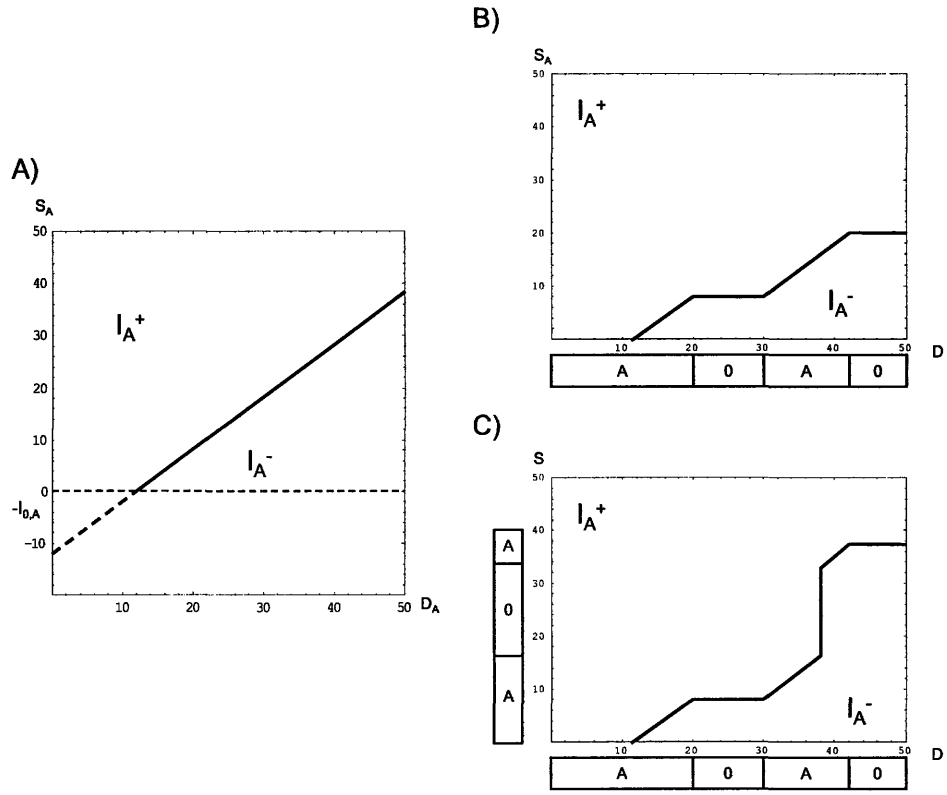

Figure 4.6: Example of bounding lines construction

A situation where S_t is large and D_t is low tends to provide positive inventory values. Therefore, the upper left side of the (S, D) space is inventory positive I_q^+. The opposite happens in the lower right side of the space, called I_q^-. There has to be a set of points (boundary line, BL) for each inventory type q for which $I_q = 0$. Its shape depends on initial inventory levels and production and demand sequences.

Assume the production and demand sequences provided by table 4.2.4 and that the initial inventory of product type A is $I_{0,A} = 11$. The BL construction process for product A is given in figure 4.6 and is based on cancelling $I_{t,q}$ term in equation (4.5) and mapping demand and supply of product q, (D_q, S_q), with total accumulated demand and supply (D, S).

Subfigure A shows the BL in a (D_A, S_A) diagram. Every point in the BL has null inventory, and therefore, has to be such that demand (D_A) equals supply (S_A) plus initial inventory $I_{0,A}$ or, alternatively, $S_A = D_A - I_{0,A}$. Note that the BL in a (D_q, S_q) space is always a 45 degrees line tranlated from the origin.

y	$q_d(y)$	Units	δ_y	z	$q_s(z)$	Units	θ_z
1	A	20	20	1	A	16	16
2	0	10	30	2	0	18	34
3	A	12	42	3		6	40
4	0	8	50				

Table 4.2: Schedule of demand (D) and supply (S)

Subfigure B draws the BL in a (D, S_q) diagram where D represents the demand for all products ($D = \sum_q D_q = D_A + D_O$). Similarly to subfigure A, the slope has to be 1 in the intervals $D \in (\delta_{y-1}, \delta y)$ for all batches y where $q_d(y) = A$ because increments ΔD imply increments ΔD_A and, therefore, increments ΔS_A in order to keep zero inventory. However, the slope is 0 in the interval $D \in (\delta_{y-1}, \delta y)$ for all batches y where $q_d(y) \neq A$ because increments ΔD do not imply an increments ΔD_A but ΔD_O.

Subfigure C draws the BL in a (D, S) diagram where S stands for the supply of all products ($S = \sum_q S_q = S_A + S_O$). It is similar to the line drawn in subfigure B in the intervals $S \in (\theta_{z-1}, \theta_z)$ for all batches z where $q_s(z) = A$ because increments ΔS_A imply increments ΔS. However, it changes in the intervals $S \in (\theta_{z-1}, \theta_z)$ for all batches z where $q_s(z) \neq A$ because increments ΔS_A imply whole 'jumps' in ΔS ($\Delta S = \theta_z - \theta_{z-1} + \Delta S_A$).

A more general description of how BL can be obtained is described in figure 4.7.

4.3 Analytic solution of the CJSP

Previous sections show the shape of JPDF at time t and how to generate BL in order to separate the I_q^+ and the I_q^- regions. Equation 4.6 shows how to calculate the probability that inventory is positive at time t given the JPDF shape at time t and I_q^+ region.

$$P_{q,t}\left(I_{q,t} > 0\right) = \iint\limits_{(x,y)\in I_q^+} f\left(y = S_t\right) f\left(x = D_t\right) dx \cdot dy \tag{4.6}$$

A scheduler needs to be able to identify the critical times t when a line has the potential of starving another process downstream. Therefore, next step is identifying the times when the result of this equation drops below a minimum non-starvation probability α. Unfortunately, the problem for this formulation is that the evaluation of this integral for each time t and each inventory type q is computationally challenging. Besides, it doesn't provide a visual insight about how the schedule can be changed in order to improve it. The following paragraphs show a visual approach to provide the scheduler with this information.

Figure 4.7: BL construction algorithm

1. Let $f_1(D_q)$ be the BL for product q in the (D_q, S_q) space:

$$f_1(D_q) = D_q - I_{0,q}$$

2. Let $f_2(D)$ be the BL in the (D, S_q) space. It is obtained from f_1 as follows:

$$f_2(D) = \begin{cases} f_1\left(D - \sum\limits_{y|\partial_y \leqslant D, q_d(y) \neq q} (\partial_y - \partial_{y-1})\right) & \text{if } q_d(y(D)) = q \\ f_1\left(\partial_{y(D)-1} - \sum\limits_{y|\partial_y \leqslant D, q_d(y) \neq q} (\partial_y - \partial_{y-1})\right) & \text{if } q_d(y(D)) \neq q \end{cases}$$

3. Let $f_3(D)$ be the BL in the (D, S) space. It is obtained from f_2 as follows:

$$f_3(D) = f_2(D) + \sum_{z|\theta_z \leqslant f_2(D), q_s(z) \neq q} (\theta_z - \theta_{z-1})$$

4.3.1 Distances-based approach

Figure 4.8 shows BL and EVL for a the example described above. The circular shapes represent a projection on the SD space of the JPDF for three different time t ($t = 1, 2.5, 5$). The dashed lines show the locus of points within two standard deviations of JPDF for different times. Note that BL is far from the dashed lines. Therefore, any integral of JPDF at any time t over the area above the BL, probability of non starvation according to 4.6, should be approximately 1. Since all JPDF's are centered on the EVL, the closer the distance between BL and EVL the lower the integral over the I_q^+ region and, therefore, the lower probability of non starvation. On the other hand, the JPDF shape flattens as time goes by, i.e., the same distance is more likely to cause starvation as time tends to higher values.

By simple observation, it can be noted that the most critical points to be considered are local minima in the distance between EVL and BL. According to equation A.8 developed in appendix A the probability of non-starvation at any of these points (D_k, S_k) can be extracted from equation 4.7, where z_α stands for the distance from the center in a standard probability density function that accumulates probability α on the left.

$$\frac{\mu_s D_k - \mu_d S_k}{\sqrt{\mu_s S_k \sigma_d^2 + \mu_d D_k \sigma_s^2}} = z_\alpha \tag{4.7}$$

Therefore, in order to validate the critical points of a certain schedule all a

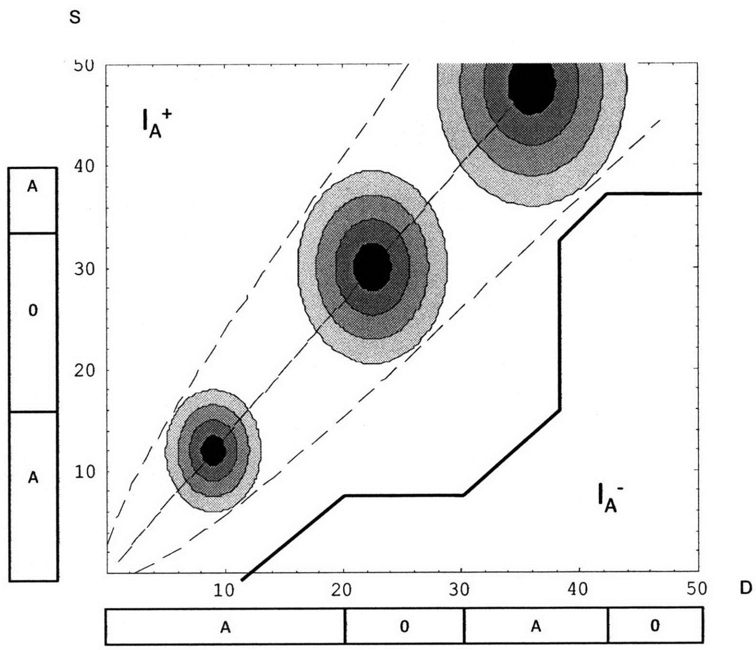

Figure 4.8: SD projection of prob. dens. func. and boundary lines

scheduler needs to do is generate the BL, extract the critical points and evaluate equation 4.7 for each of them. Furthermore, a scheduler can get some insights about how to improve the schedule by simple observation of the corresponding DS diagram.

4.4 CJSP Case study

Consider the environment described in the introduction where one assembly group (B) is supplied by a carrier machining group (A). Both groups are mixed-product, i.e., they manufacture different product types: G-9, G-6 and G-3.

Assume that a scheduler has to establish the schedule for the upstream process (A) given an expected schedule in group (B) provided by table 4.4 and initial inventories as in table 4.4.

Groups A and B can build at rates of $\mu_d = 2700$ and $\mu_s = 3000$ units/day respectively and their standard deviations are similar $\sigma_d \approx \sigma_s = 600$ units/day. The supplier group is faster but, due to its longer setup times (equivalent to 300 units), B cannot follow the schedule given by line A. Instead, given that there is enough initial inventory to feed A, B can try to build weekly batches, i.e., run the weekly demand for each product sequentially. Table 4.5 and figure 4.9 show the supply schedule and expected inventory profile under this scenario. Note that

y	q	Units	δ_y
1	G-9	900	900
2	G-6	600	1500
3	G-3	300	1800
4	G-9	1800	3600
5	G-6	600	4200
6	G-3	300	4500
7	G-9	1800	6300
8	G-6	600	6900
9	G-3	300	7200
10	G-9	1800	9000
11	G-6	600	9600
12	G-3	300	9900
13	G-9	1800	11700
14	G-6	600	12300
15	G-3	300	12600
16	G-9	1800	14400

Table 4.3: Demand schedule

q	$I_{0,q}$
G-9	3600
G-6	900
G-3	0

Table 4.4: Initial inventory levels

production of a fake product (0) is used to simulate changeovers.

z	q	Units	θ_z
1	G-3	1500	1500
2	0	300	1800
3	G-6	2100	3900
4	0	300	4200
5	G-9	9000	13200

Table 4.5: Supply schedule

Unfortunately, the profile provided in figure 4.9 doesn't help the scheduler much because it doesn't provide information about how likely is line A of starving line B or which the most critical times are going to be. It seems like the most critical point (called point 0 below) is expected to happen at time $t = 0.6$ days with expected inventory level of 200 units. At this time, G-6 inventory has been demanded for several hours but no supply has been provided.

A DS diagram for this schedule as provided by figure 4.10 can provide more

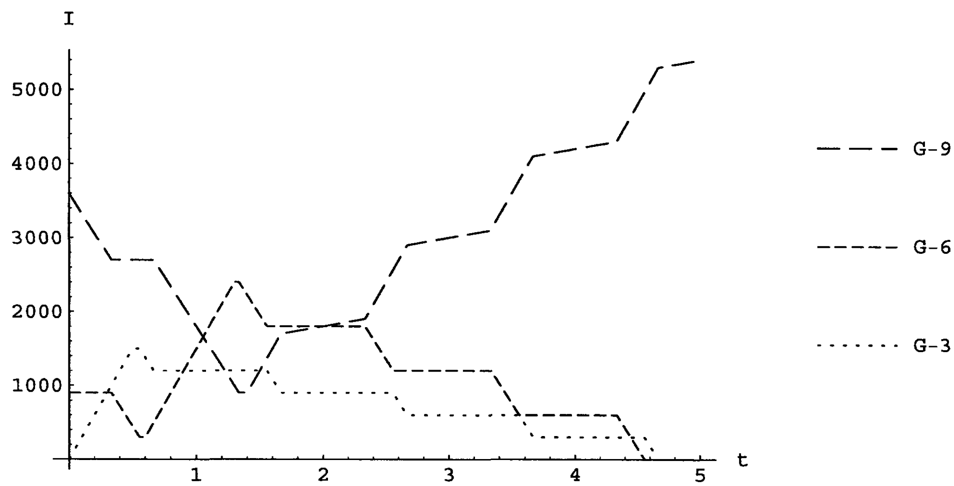

Figure 4.9: Inventory profile given expected schedule

useful information. It is visually clear which are the most critical events to be considered. In this case, the closest points to the EVL are A and B, the times when G-9 starts being produced again and when it stops being demanded respectively. The probability of starving the line at point $A = (5400, 4200)$ according to equation 4.7 is:

$$\begin{aligned} P_A &= z^{-1}\left(\frac{\mu_s D_k - \mu_d S_k}{\sqrt{\mu_s S_k \sigma_d^2 + \mu_d D_k \sigma_s^2}}\right) \\ &= z^{-1}\left(\frac{3000\cdot5400 - 2700\cdot4200}{\sqrt{3000\cdot4200\cdot600^2 + 2700\cdot5400\cdot600^2}}\right) \\ &= z^{-1}(1.554) \\ &= 7\% \\ P_B &= 6.9\% \end{aligned}$$

According to this framework, point 0, identified as a critical point in figure 4.9, has approximately null probability of starvation ($P_0 = z^{-1}(5.603) \approx 10^{-8}$).

In this context a scheduler has two options: accepting the result or trying to improve it. If a new schedule is considered, the DS diagram can help to decide how to modify the schedule. It is clear in figure 4.10 that point A has to be moved away from the EVL. In order to do so, a certain amount of G-9 product can be inserted on the line before all the G-6 is finished. Figure 4.11 provides a solution with these two additional changeovers. As expected, points A and B are moved away from the EVL the corresponding probabilities of starvation are now below 2%. This solution might have solved the starvation problems for product G-9 but might have disturbed other products' schedule. Note that points C and D,

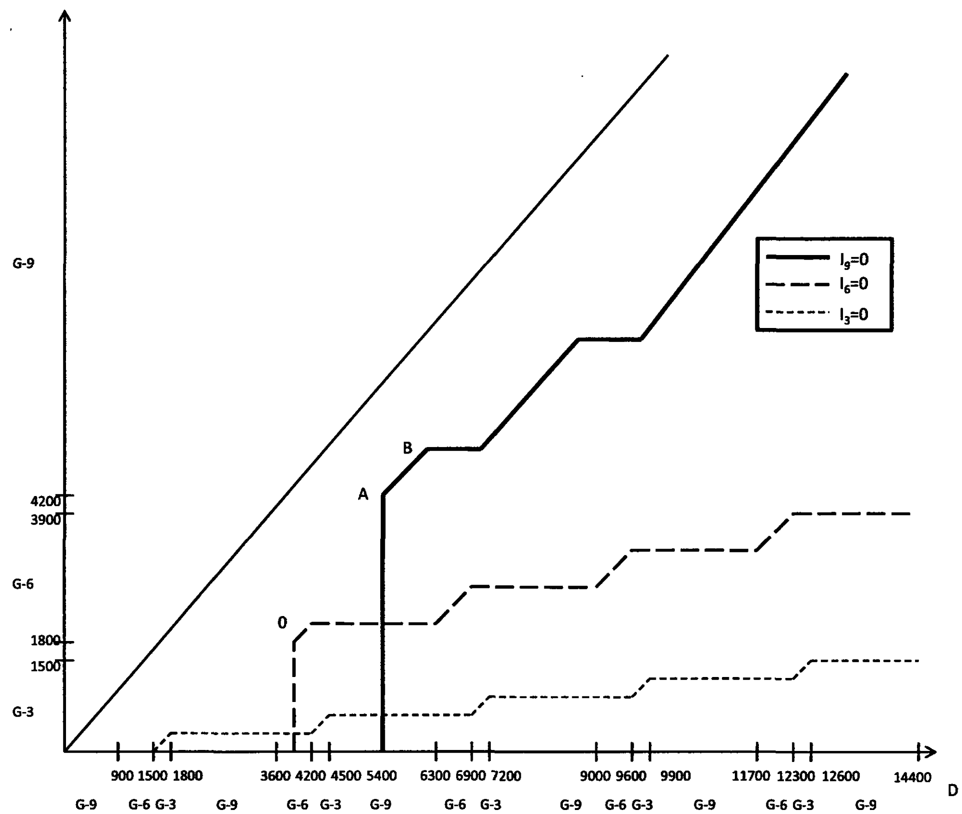

Figure 4.10: First DS diagram

corresponding to the events when line A starts to build G-6 for the second time, are now much closer to the EVL but never become more critical than points A and B.

4.5 Conclusion

This chapter has described two major improvement initiatives in the component machining and welding area.

First section describes a new kanban-system for the tube machining and welding operation and how some of the major challenges that had made it fail in previous attempts were addressed.

The remaining sections concentrate on the carrier job inventory management policy. Section 2 provides a thorough description of the problem faced by an scheduler of the carrier job and why the kanban system approach that worded in other operations would fail in this one.

Sections 3 and 4 provide an analytic framework for the problem, proposes

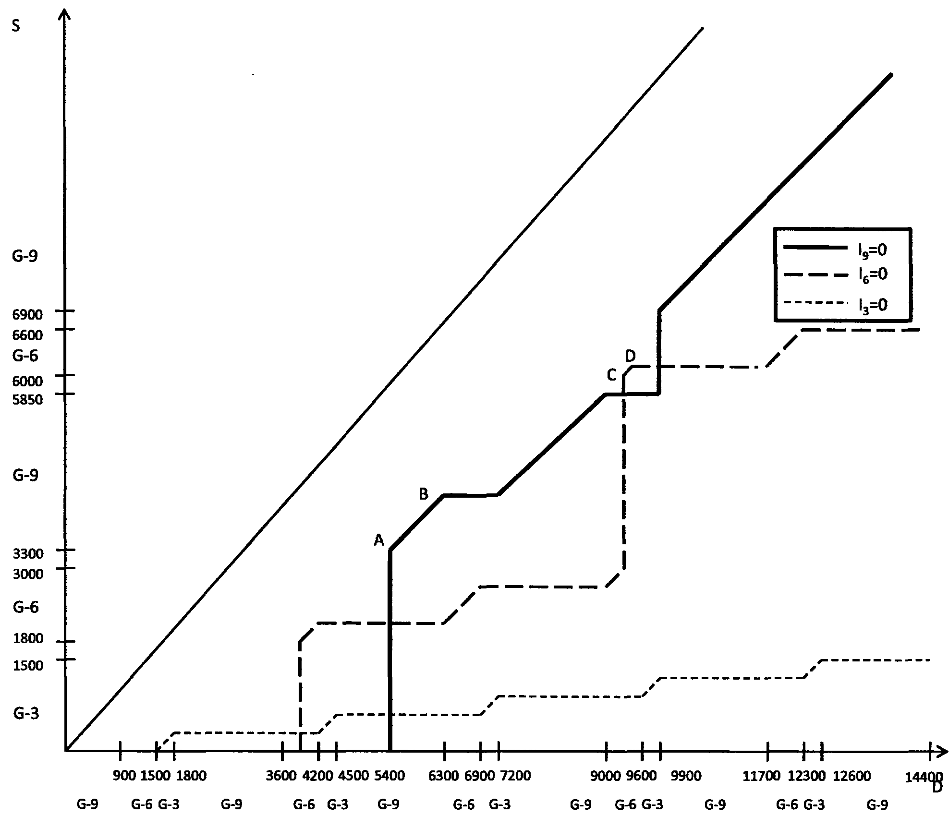

Figure 4.11: Second DS diagram

a new approach to it and show a case study that resembles the conditions of the carrier job. Note that this result provides a valuable tool to the material flow management literature as it provides a visual diagram to quickly identify the most critical events and how to change schedules in order to minimize their likelihood.

Chapter 5

Conclusion

5.1 Conclusion

This document describes some of the improvement efforts carried out in the Plant 2 Detroit Gear & Axle facility of American Axle & Manufacturing Inc in the period between June 2007 and December 2007.

Chapters 1 and 2 provide some background about AAM and about the state of the art in modern manufacturing systems.

Chapter 3 is dedicated to a Heijunka system implemented in the assembly area. It describes how the material flow, material requirements and communication systems were improved, what the major leadership and strategical challenges were and some recommendations to improve the current system.

Chapter 4 is dedicated to the improvements in the component machining area. First section describes the new kanban system for the tube job. Again, it concentrates on the major challenges that made previous development attempts fail and how these were addressed. The following sections provide a description of the carrier job problem and why it could not be solved by means of kanban systems. They also provide a new visual framework to generate schedules for this job.

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Appendices

Appendix A

Distances based approach

The goal is to provide an estimation of the probability of starvation at any critical point t_k. Equation A.1 expands equation 4.6 with the probability density function of normal distributions. Note that distances on the S axis are divided by σ_s whereas those on the D axis are divided by σ_d. In order to normalize the amount of probability associated with distance in each axis both axes have been re-scaled in equation A.2. This way, the oval in figure 4.8 is re-shaped into a circle. All the symbols noted with a prime $'$ reference the same symbol after it have been re-scaled.

$$\begin{aligned} &\iint\limits_{I_q^+} f\left(S=y, D=x\right)_t dy \cdot dx \\ &= \iint\limits_{I_q^+} \frac{1}{\sigma_s \sigma_d 2\Pi t} e^{\left(-\frac{(y-\mu_s t)^2}{2\sigma_s^2} - \frac{(x-\mu_d t)^2}{2\sigma_d^2}\right)} dy \cdot dx \end{aligned} \tag{A.1}$$

$$\begin{aligned} &\iint\limits_{I_q^+} \frac{1}{\sigma_s \sigma_d 2\Pi t} e^{\left(-\frac{(y-\mu_s t)^2}{2\sigma_s^2} - \frac{(x-\mu_d t)^2}{2\sigma_d^2}\right)} dy \cdot dx \quad \underset{\left[\begin{array}{cc} y' = \frac{y}{\sigma_s} & \mu_s' = \frac{\mu_s}{\sigma_s} \\ x' = \frac{x}{\sigma_d} & \mu_d' = \frac{\mu_d}{\sigma_d} \end{array}\right]}{=} \\ &\iint\limits_{I_q^{+'}} \frac{1}{2\Pi t} e^{-\frac{1}{2}\left((y'-\mu_s' t)^2 + (x'-\mu_d' t)^2\right)} dy' \cdot dx' \end{aligned} \tag{A.2}$$

Let the result of equation A.2 integrated over $I_q^{+'}$ be $P_{t,I_q^{+'}}$. By simple observation it can be noticed that the most likely times where $P_{t,I^{+'}}$ can reach its minimum value are local minima in the distance between EVL and BL. Let the those points in BL' be called critical points, noted (S'_k, D'_k) and let t'_k be the corresponding times obtained by projecting these points on EVL.

Let $I^*_{t_k,q}$ be an approximation of $I^{+'}_q$ that contains all the region above a parallel to EVL that crosses through (S'_k, D'_k). $P_{t_k,I^{+'}}$ is greater than $P_{t_k,I^*_{t_k}}$ because (S'_k, D'_k) has been chosen as a local minimum in the distance between EVL and BL and, therefore, $I^*_{t_k}$ contains $I^{+'}$. As a conclussion, it can be stated that $P_{t,I^*_{t_k}}$ is a conservative estimate of $P_{t,I^{+'}}$.

$P_{t_k,I^*_{t_k}}$ can be easily computed with the cumulative density function of a normal distribution with average 0 and standard deviation proportional to $\sqrt{t_k}$ at distance l_k (distance between the SEV line and (D_k, S_k)). Distance l_k and time t_k can be computed as functions of (D'_k, S'_k) and the expected demand (d') and production (s') per shift by geometric analysis of figure A.1.

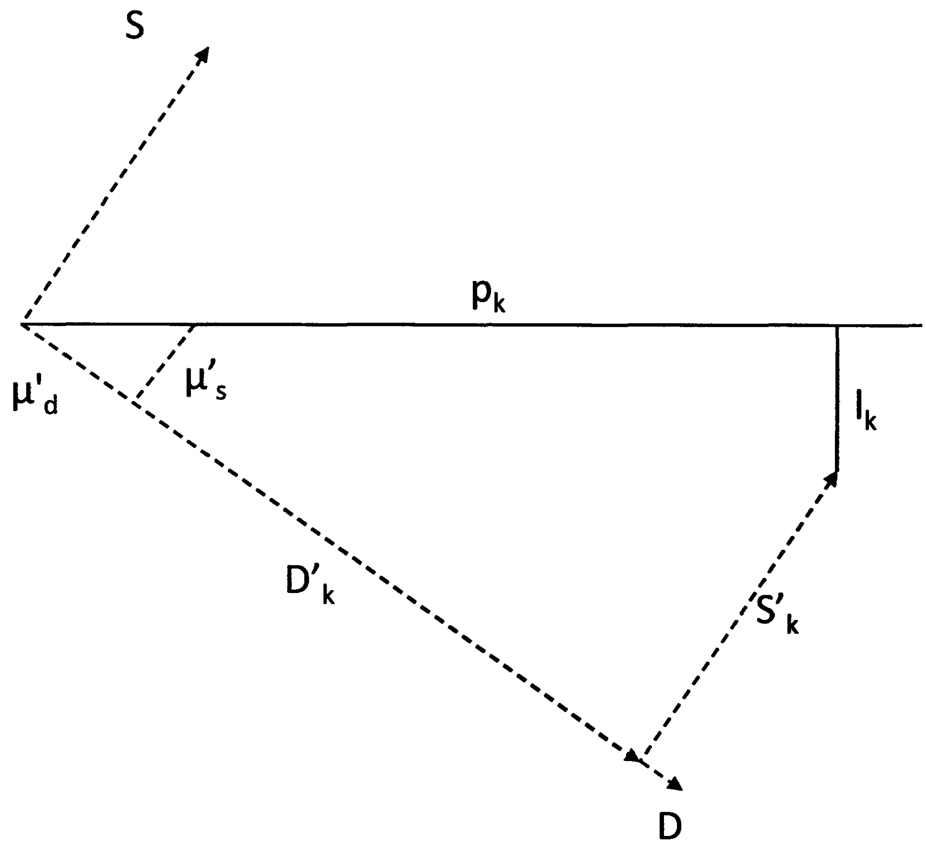

Figure A.1: Geometric calculation

$$l_k = D'_k \frac{\mu'_s}{\sqrt{\mu'^2_d + \mu'^2_s}} - S'_k \frac{\mu'_d}{\sqrt{\mu'^2_d + \mu'^2_s}} \tag{A.3}$$

$$t_k = \frac{p_k}{\sqrt{\mu^2_d + \mu^2_s}} = D'_k \frac{\mu'_d}{\mu'^2_d + \mu'^2_s} + S'_k \frac{\mu'_s}{\mu'^2_d + \mu'^2_s} \tag{A.4}$$

Let α be the probability of non-starvation. The following equation has to hold for all points (D'_k, S'_k).

$$P_{t_k, I^*_{t_k}} = CDF(0, \sqrt{t_k})_{l_k} = \alpha \tag{A.5}$$

$$\frac{l_k}{\sqrt{t_k}} = z_\alpha \tag{A.6}$$

$$\frac{D'_k \mu'_s - S'_k \mu'_d}{\sqrt{D'_k \mu'_d + S'_k \mu'_s}} = z_\alpha \tag{A.7}$$

$$\frac{\mu_s D_k - \mu_d S_k}{\sqrt{\mu_s S_k \sigma^2_d + \mu_d D_k \sigma^2_s}} = z_\alpha \tag{A.8}$$

List of Symbols and Abbreviations

Abbreviation	Description	Definition
3M	3rd member	page 12
3MB	3rd member bank	page 12
FGI	Finished goods inventory	page 22
FTQ	First Time Quality	page 30
Heijunka	Level Schedule	page 22
JIT	Just in Time	page 21
Kanban	Card	page 20
LL	Final assembly line	page 12
MRP	Materials Requirement Planning	page 23
NW	North 3M line	page 12
SW	South 3M line	page 12
TPS	Toyota Production System	page 19

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